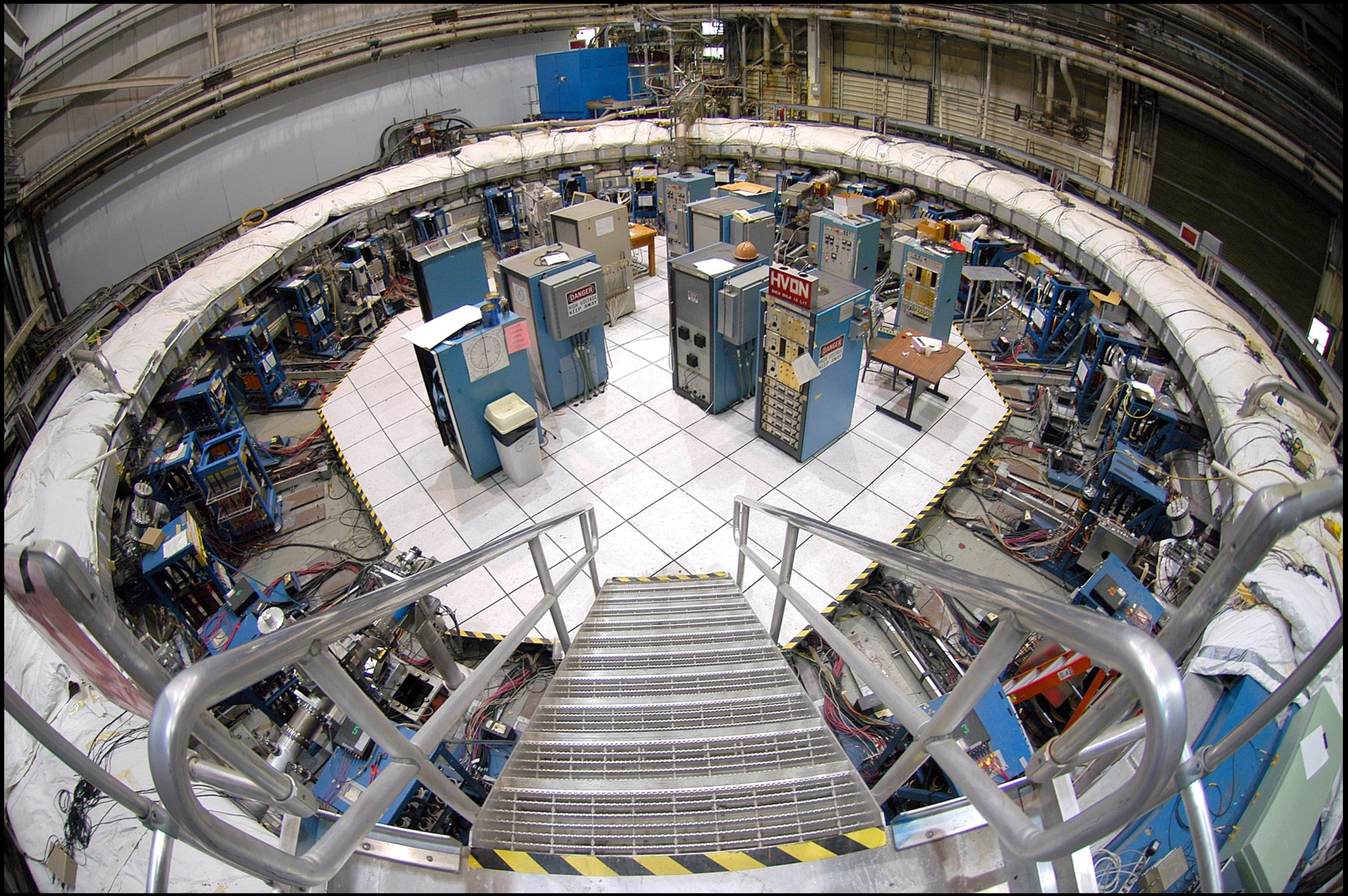
Bringing Muon g-2 to Fermilab

Chris Polly, Fermilab



Outline for today...

- Brief history of lepton magnetic moments
- Principles enabling modern day muon g-2 experiments
- SM calculation of a
- Strategy for mounting a muon g-2 experiment at FNAL
- Status of the project/current events

A brief history tour...

- Fundamentally, the magnetic moment can be described by thinking about the interaction of a current loop in magnetic field

$$\vec{\tau} = \vec{\mu} \times \vec{B}, \quad U = -\vec{\mu} \cdot \vec{B}$$

- A current loop in a magnetic field experiences a torque proportional to the field strength and the magnetic moment...can simply calculate μ

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c} \vec{L}_i$$

- Classically one can try to treat the electron spin $\vec{S} = \frac{\hbar}{2}\vec{\sigma}$ as an angular momentum

$$\vec{\mu} = g \frac{q\hbar}{4mc} \vec{\sigma}, \text{ where } g = 1$$

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$$g_e \approx 2$$

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- Since the early 1920s, it was know from Stern-Gerlach and atomic spectroscopy measurements that...

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Magnetic moments have been surprising us ever since!

Dirac to the rescue!

- The solution to the electron g problem did not appear until 1928 when Dirac essentially writes down the master equation governing a spin ½ point particle.

$$\left(\frac{1}{2m}(\vec{P}+e\vec{A})^2+\frac{e}{2m}\vec{\sigma}\cdot\vec{B}-eA^0\right)\psi_A=(E-m)\psi_A$$

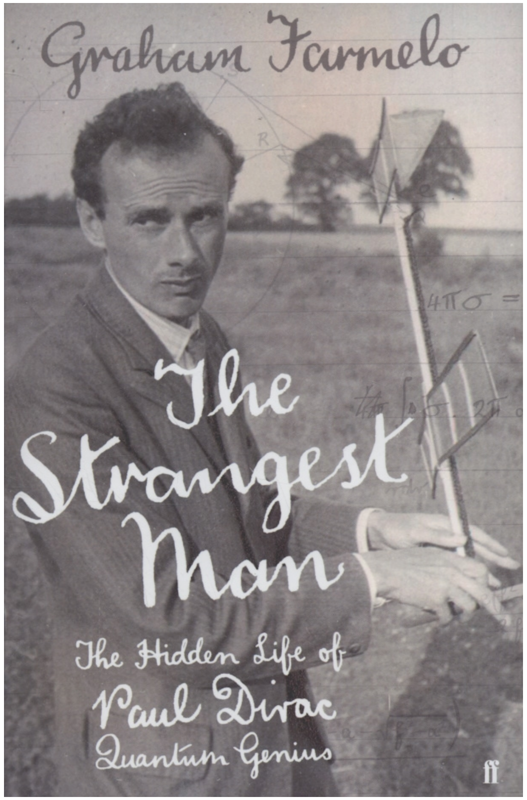
- Comparing the $\vec{\sigma}\cdot\vec{B}$ term to the classical analogue

$$\mu=-\frac{e}{2m}\vec{\sigma}$$

So, for an elementary particle in Dirac's theory, g=2!

- Interesting aside: soon after (1933) Stern and Estermann were out to measure the g-factor for the proton *"Don't you know the Dirac theory? It is obvious that g_p=2."*, Pauli to Stern

- Stern and Estermann found...



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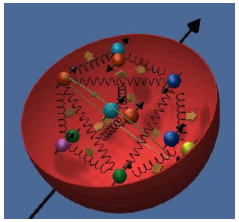
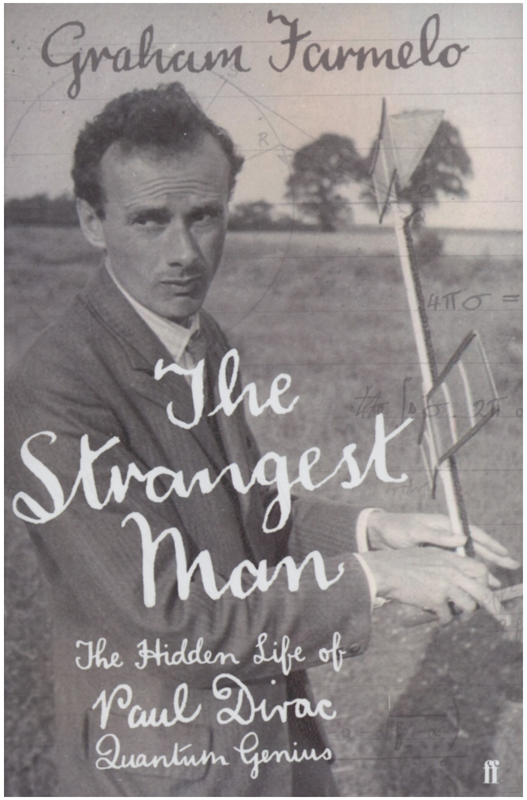
$g_p \approx 5.6$





Same year, Rabi inferred g_n=-3.8 from deuteron!

Proton and neutron substructure!

Proof that nature abhors a vacuum...

- At least for the electron, things were finally in good shape with Dirac's new theory until 1948 when gains in precision revealed an 'anomaly'

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Thus the 'anomaly' was discovered, fractionally g differs from 2 by $(g-2)/2 = 0.1\%$

$$g_e = 2.00238(6)$$

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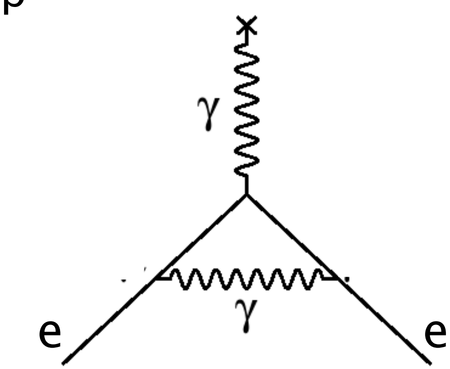
$g_e = 2.00238(6)$

- Schwinger takes one look at that g-factor and immediately knows what's up



$$g_e \approx 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$

And so QED was 'discovered'

Fast forward 60 years into the future of a_e...

- QED now calculated out to 5^{th} order in α

$a_e^{SM} = (1/2)(\alpha/\pi) - 0.328\ 478\ 444\ 002\ 90(60)\ (\alpha/\pi)^2$

Schwinger 1948 — Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '06

$A_2^{(4)}(m_e/m_\mu) = 5.197\ 386\ 70\ (28) \times 10^{-7}$

$A_2^{(4)}(m_e/m_\tau) = 1.837\ 62\ (60) \times 10^{-9}$

$+\ 1.181\ 234\ 016\ 827\ (19)\ (\alpha/\pi)^3$

Kinoshita, Barbieri, Laporta, Remiddi, ... , Li, Samuel; Mohr & Taylor '05; MP '06

$A_2^{(6)}(m_e/m_\mu) = -7.373\ 941\ 64\ (29) \times 10^{-6}$

$A_2^{(6)}(m_e/m_\tau) = -6.5819\ (19) \times 10^{-8}$

$A_3^{(6)}(m_e/m_\mu, m_e/m_\tau) = 1.909\ 45\ (62) \times 10^{-13}$

$-\ 1.9144\ (35)\ (\alpha/\pi)^4$

Kinoshita & Lindquist '81, ... , Kinoshita & Nio '05; Aoyama, Hayakawa, Kinoshita & Nio, June '07

$+\ 0.0\ (4.6)\ (\alpha/\pi)^5$ In progress (12672 mass ind. diagrams!)

Mohr & Taylor '05; Aoyama, Hayakawa, Kinoshita, Nio & Watanabe, June 2008 (more in progress).

$+\ 1.682\ (20) \times 10^{-12}$ Hadronic

Mohr, Taylor & Newell '08; Davier & Hoecker '98, Krause '97, Knecht '03

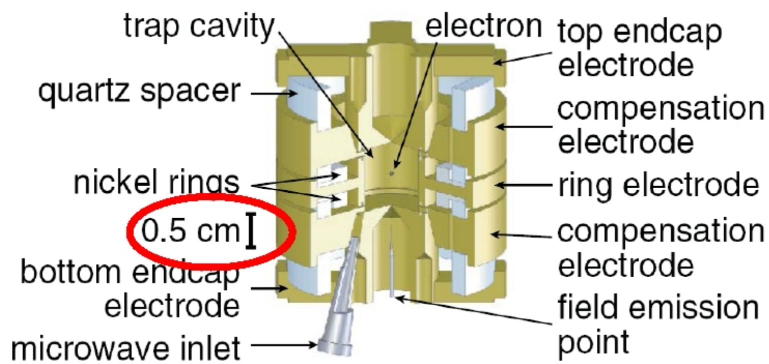
$+\ 0.0297\ (5) \times 10^{-12}$ Electroweak

Mohr & Taylor '05; Czarnecki, Krause, Marciano '96

*Summary by M. Passera, INT 28 Oct 2009

...and a new experimental result for a_e

- Gabrielse's group at Harvard employ an ultra-precise Penning trap



$$a_e^{exp} = 1159652180.73\ (28) \times 10^{-12}$$ Hanneke et al, PRL100 (2008) 120801

- Can take α from external measurements and be used to test QED at 4 loops

$\alpha^{-1} =$	137.036 000 00	(110)	[8.0 ppb]	PRA73 (2006) 032504 (Cs)
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- Or, assume g_e calculable in SM and extract a with sub-ppb precision

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δC_4^{qed} δC_5^{qed} δa_e^{had} δa_e^{exp} (smaller than th!)

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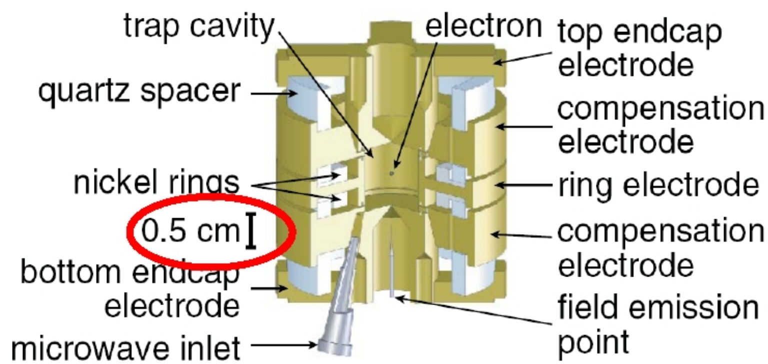

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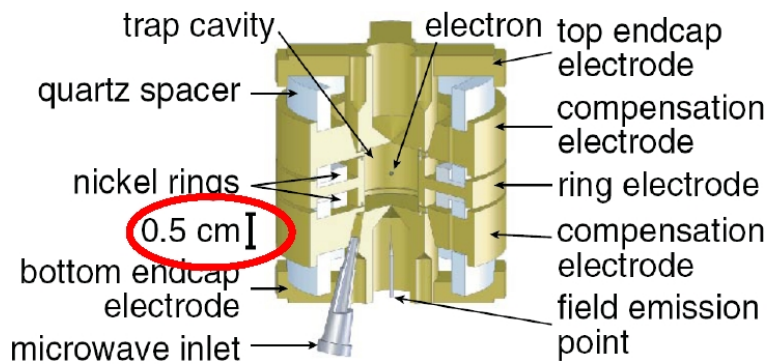

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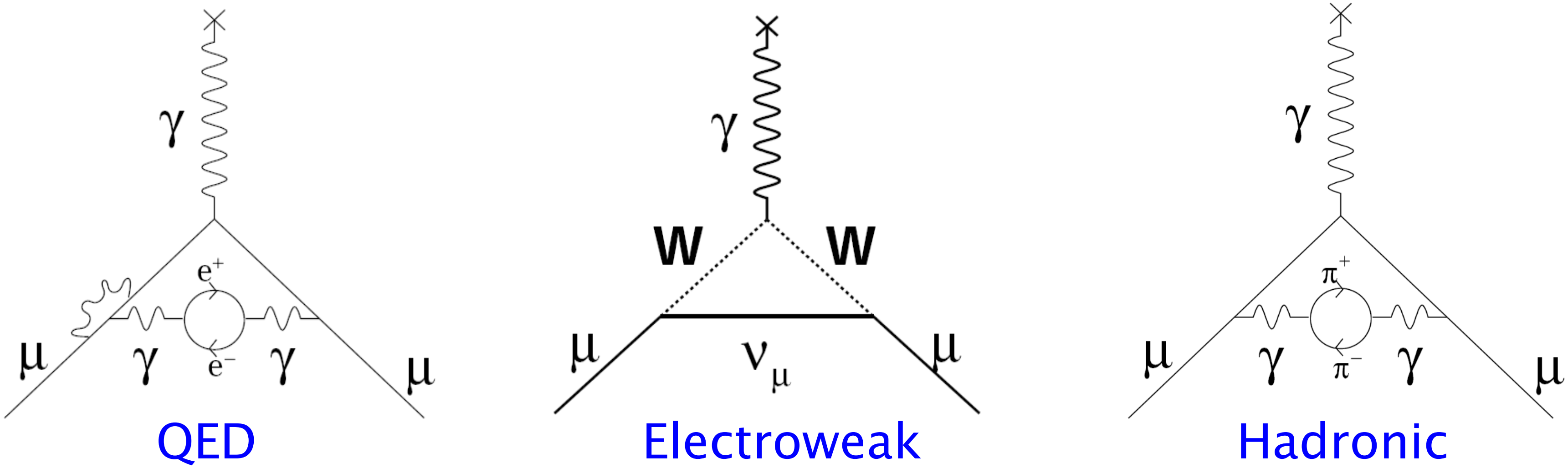
That brings us to the muon anomaly $a_\mu = \frac{g-2}{2}$



- It is common to break the SM contribution into various sources

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP}$$

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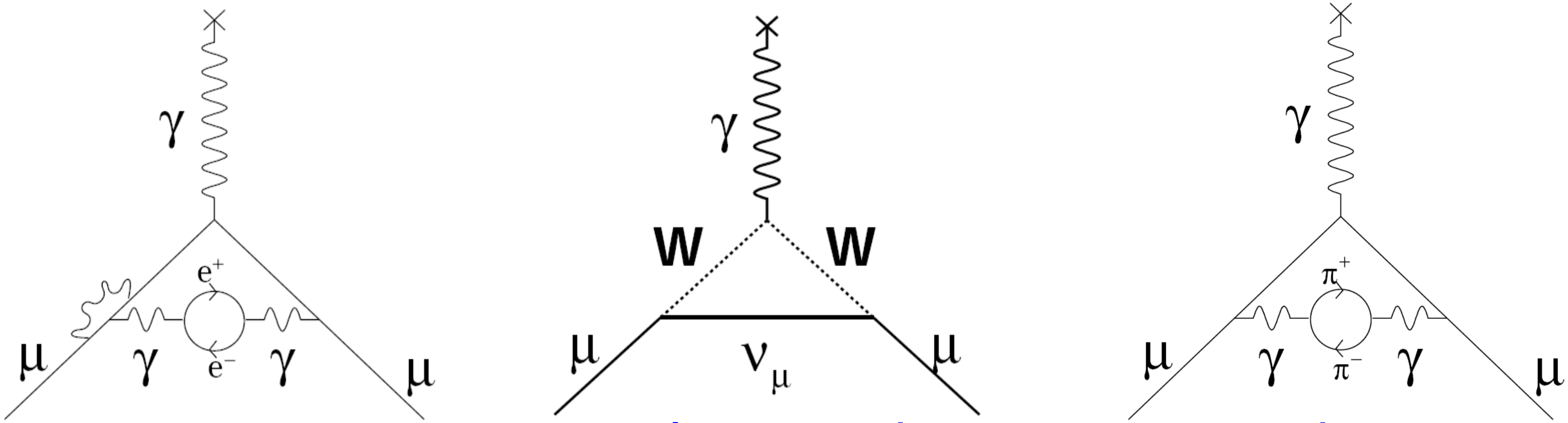

QED | Electroweak | Hadronic

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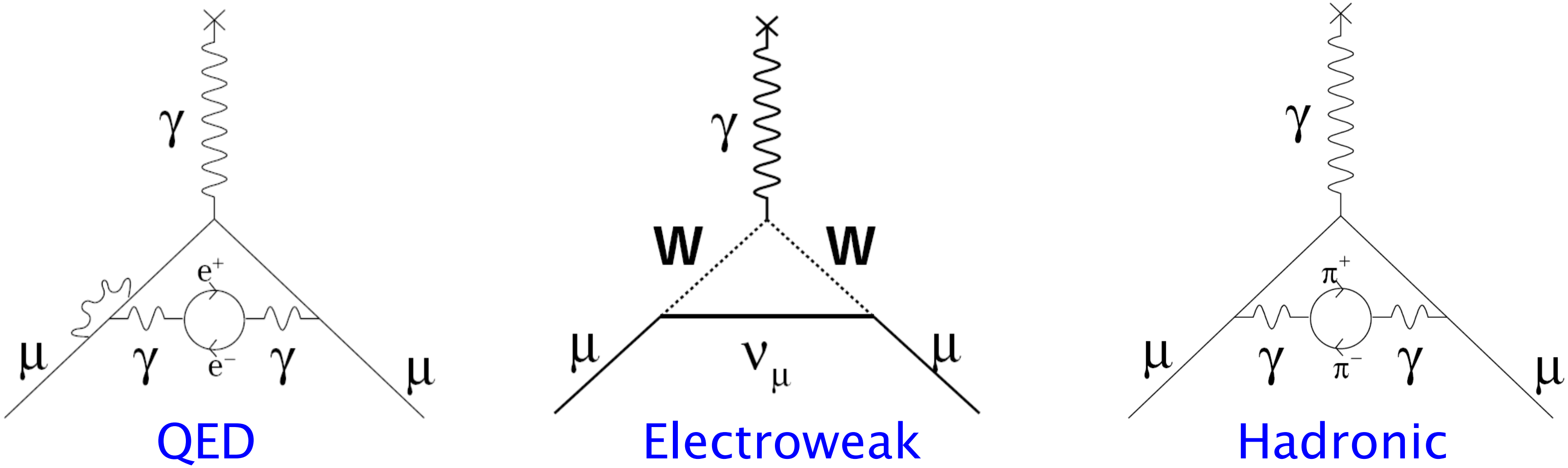

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$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$

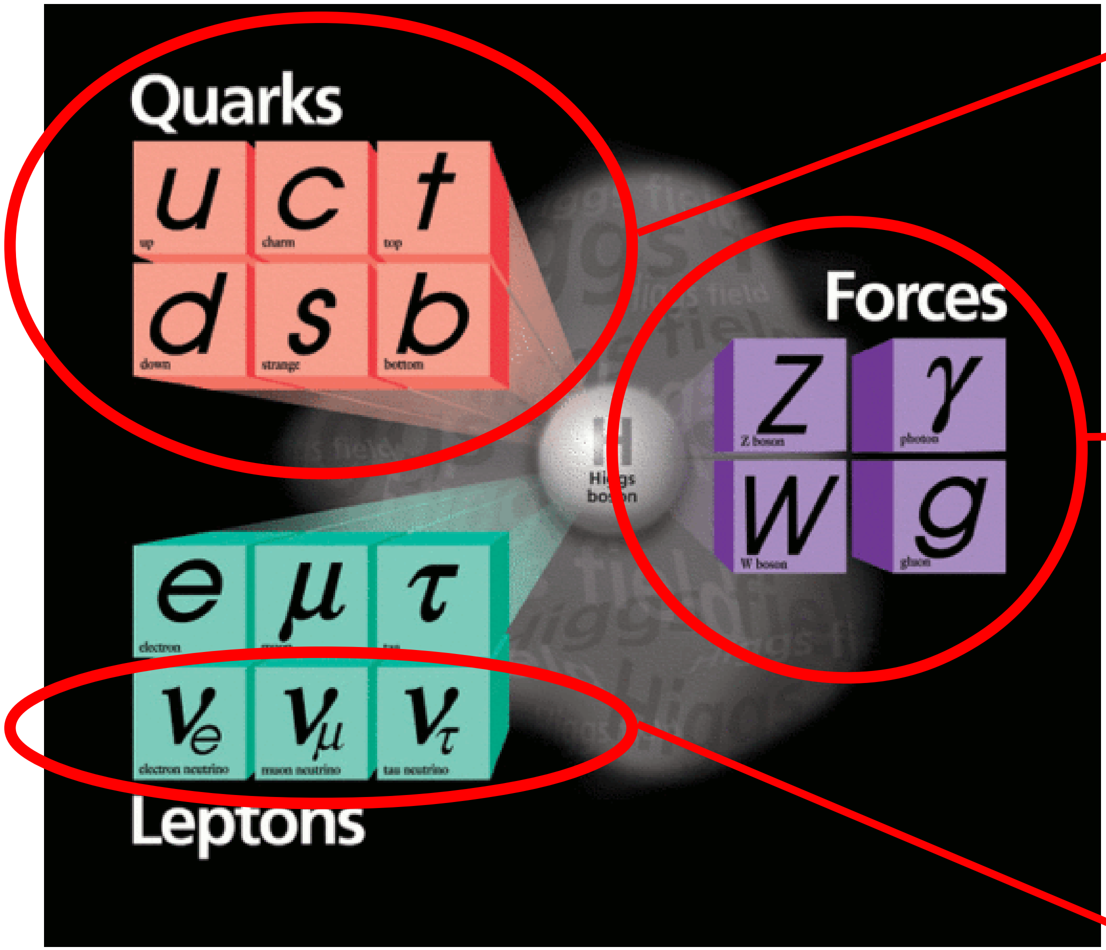
- Provides an EXTREMELY SENSITIVE and GENERAL probe of higher mass exchanges

$$\lambda_{sens} \propto \left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$$

*Makes up for x1000 better precision of a_e

> Fortuitous Physics Fact #1: The muon is heavy enough to give us a large enhancement, but still lives long enough (2.2 μs) to be measured.

The muon is unique in this role among fundamental particles

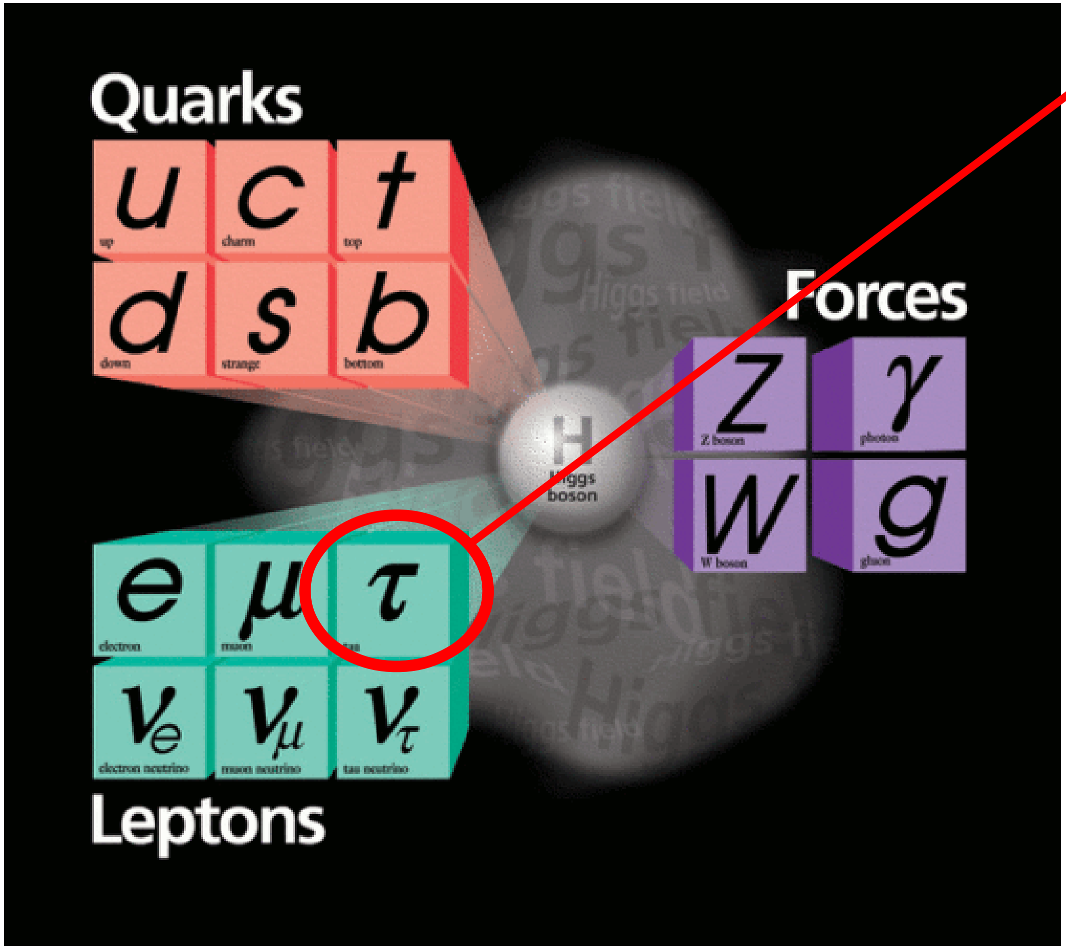


Only exist as complictated multi-body objects

Too fleeting or no electric charge

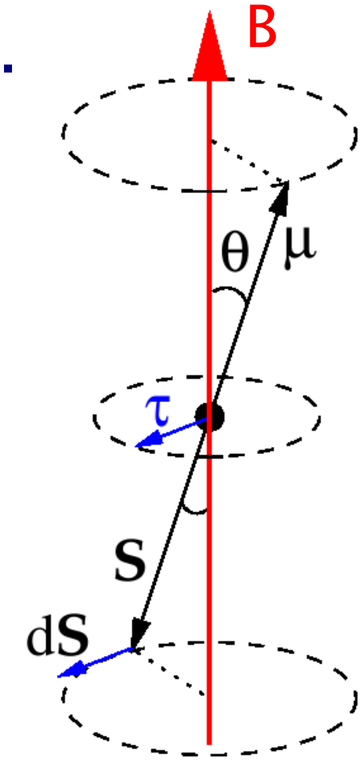
Neutral (and too light)

The muon is unique in this role among fundamental particles



- m_τ =1777 MeV, m_μ=106 MeV
- $(m_\tau/m_\mu)^2 \approx 280$
- τ meson has heightened sensitivity to higher-mass exchanges
- But, 290 femtosecond lifetime is smaller by a factor of 7.5 million compared to muon
- Limits current precision to
  - $-0.052 < a_\tau < 0.013$

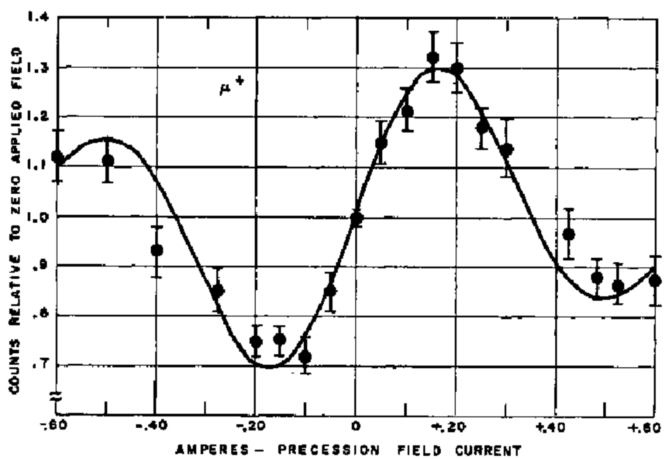
Early experimental techniques...



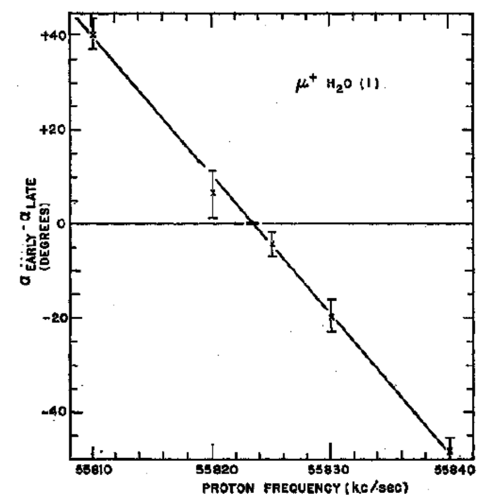
- Simplest way to measure the muon magnetic moment is to make some muons, put them in a field and measure the Larmor precession frequency

$$\omega_s = g\frac{eB}{2mc}$$

- That is exactly what Garwin did in 1957...g_μ=2.00 ± 0.10



- Series of Larmor precession measurements ended with Hutchinson (1963). Measuring to ω_s and B to <10 ppm. precision...unfortunately limited by 100 ppm m_μ precision



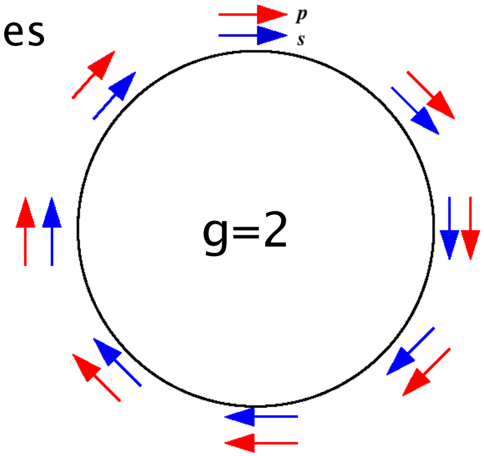
New idea! Measure spin precession in a cyclotron

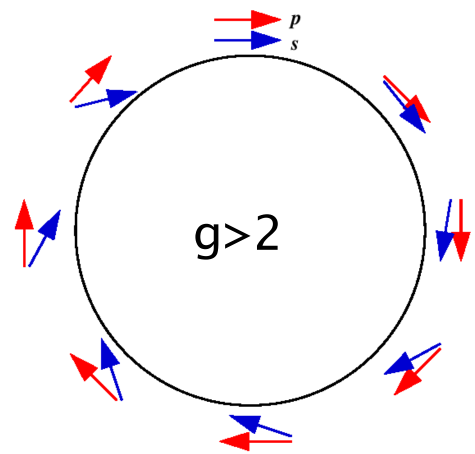
- Taking the difference of the cyclotron and Larmor frequencies

$$\omega_s = g\frac{eB}{2mc}$$

$$\omega_c = \frac{eB}{mc}$$

$$\begin{aligned}\omega_a &= \omega_s - \omega_c, \\ &= \frac{eB}{mc}\left(\frac{g}{2}-1\right), \\ &= \frac{eB}{mc}\frac{g-2}{2}, \\ &= a_\mu \frac{eB}{mc},\end{aligned}$$





- Interesting that the difference is directly proportional to only the anomalous part, a_μ
- Measuring a_μ directly determines everything after the decimal place in g_μ=2.00232...800 x the precision for free!
- Also means B can be known with factor of 800 less precision, for same precision in g_μ

Fortuitous Physics Fact #2: The difference $\omega_a = \omega_s - \omega_c$ is directly proportional to the anomaly, a_μ.

What about the muon mass?

- Start by making some definitions/observations

$$\omega_s = g\frac{eB}{2mc}$$

$$\omega_c = \frac{eB}{mc}$$

$$\begin{aligned}\omega_a &= \omega_s - \omega_c, \\ &= \frac{eB}{mc}\left(\frac{g}{2} - 1\right), \\ &= \frac{eB}{mc}\frac{g-2}{2}, \\ &= a_\mu \frac{eB}{mc},\end{aligned}$$

$$\boxed{\begin{aligned}\frac{\omega_a}{\omega_s} &= \frac{a_\mu}{a_\mu + 1} \\ \frac{\omega_a}{\omega_s} &= \frac{\omega_a}{\omega_p}\frac{\omega_p}{\omega_s} \\ \lambda = \frac{\omega_\mu}{\omega_p} &= \frac{\mu_\mu}{\mu_p} \\ \Re &= \omega_a/\omega_p\end{aligned}}$$

- Can now rewrite a_μ as $\boxed{a_\mu = \frac{\Re}{\lambda - \Re}}$

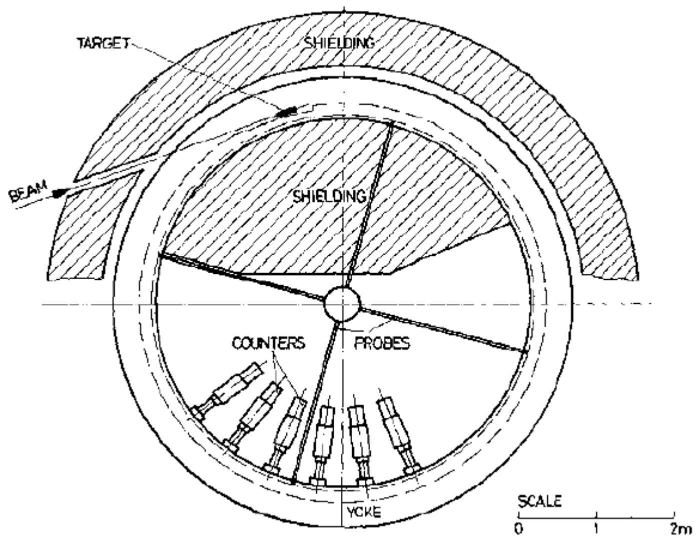
Note: $\omega_s = \omega_\mu = \mu$ Larmor freq
ω_p = proton Larmor freq

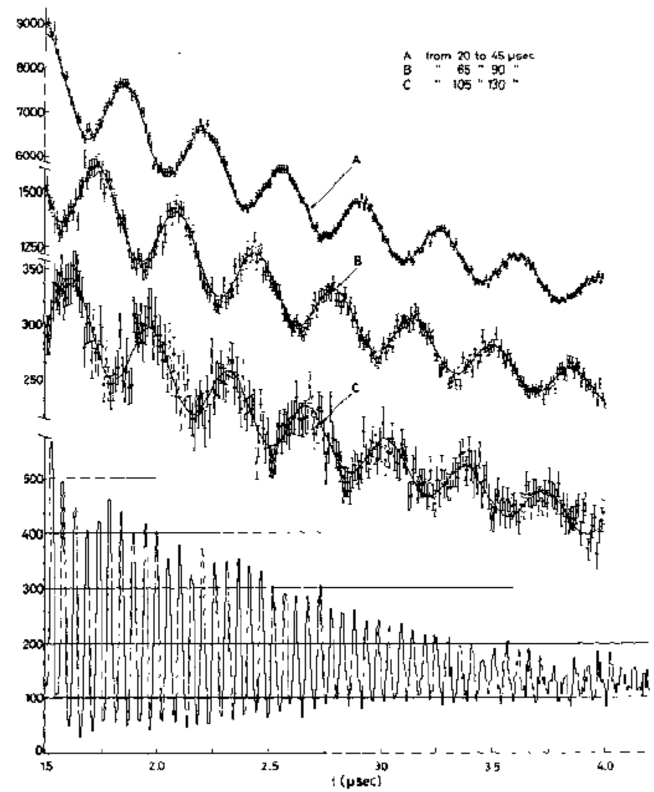
- Determine $\Re$ in a dedicated muon g-2 experiment, and λ is know to 120 ppb from muonium hyperfine spectroscopy.

Fortuitous Physics Fact #3: Can use muonium hyperfine spectroscopy to eliminate dependence on muon mass measurement.

All 3 (+2 more) 'Fortuitous Physic Facts' used by CERN II

- CERN I (not a ring) measured a_μ to 4300 ppm...validating QED at 2nd order
- CERN II measured a_μ to 270 ppm...testing QED to 3rd order, initial discrepancy resolved by mistake in QED light-by-light diagrams





CERN II Setup &
the first 'wiggle plot'

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$

CERN III and the BNL experiment use one last trick!

- To keep muons confined vertically in the storage ring, an electric field must be applied, thus modifying the equation for a_μ

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

- This leads us to the most fortuitous physics fact in modern muon g-2 expts...

Fortuitous Physics Fact #6: The size of the anomaly is just right, choosing γ=29.3 (p_μ=3.09 GeV/c) the coefficient in front of the electric field cancels ('magic p').

- Means electric field (much harder to measure than B field) can be used
  - Had a_μ been much **smaller**, γ could have been too large to produce a sufficient flux of muons or contain them in a reasonable-sized ring.
- CERN III used this technique to start probing hadronic contributions

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It is because of these fortuitous physics facts that you often see muon g-2 referred to as a classic 'textbook' experiment!!

Final stop on the history tour…Brookhaven

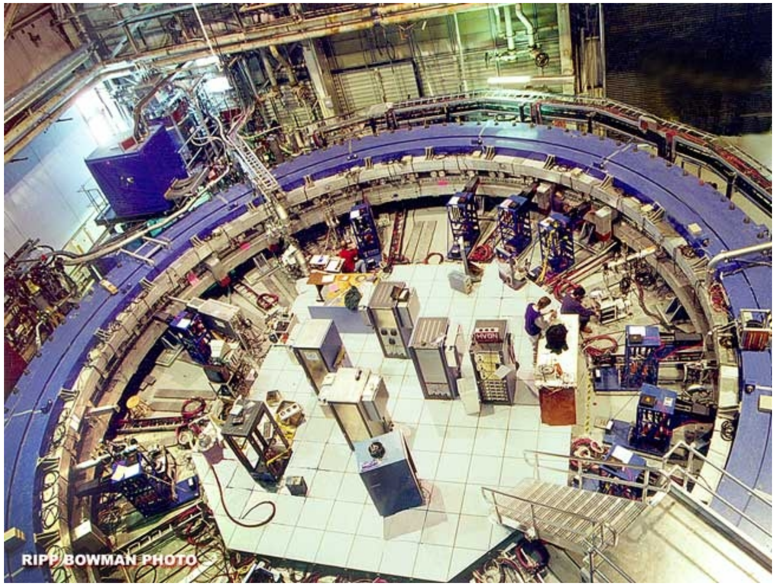
- These gentlemen decided to use many technological innovations to tap the potential of the magic momentum method to improve our knowledge of a_μ

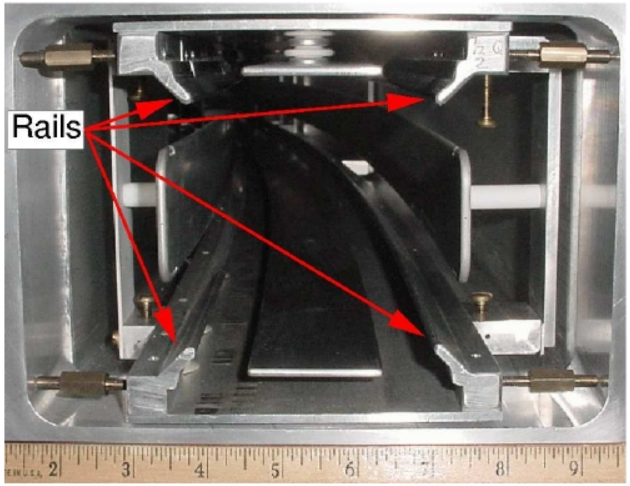
Figure 1.10: A picture from 1984 showing the attendees of the first collaboration meeting to develop the BNL g-2 experiment. Standing from left: Gordon Danby, John Field, Francis Farley, Emilio Picasso, and Frank Krienen. Kneeling from left: John Bailey, Vernon Hughes and Fred Combley.

Final stop on the history tour...Brookhaven

- By the mid 1990s, the collaboration had grown substantially. The new BNL storage ring was constructed and ready for its first engineering run in 1997

First engineering run in 1997, last physics run in 2001





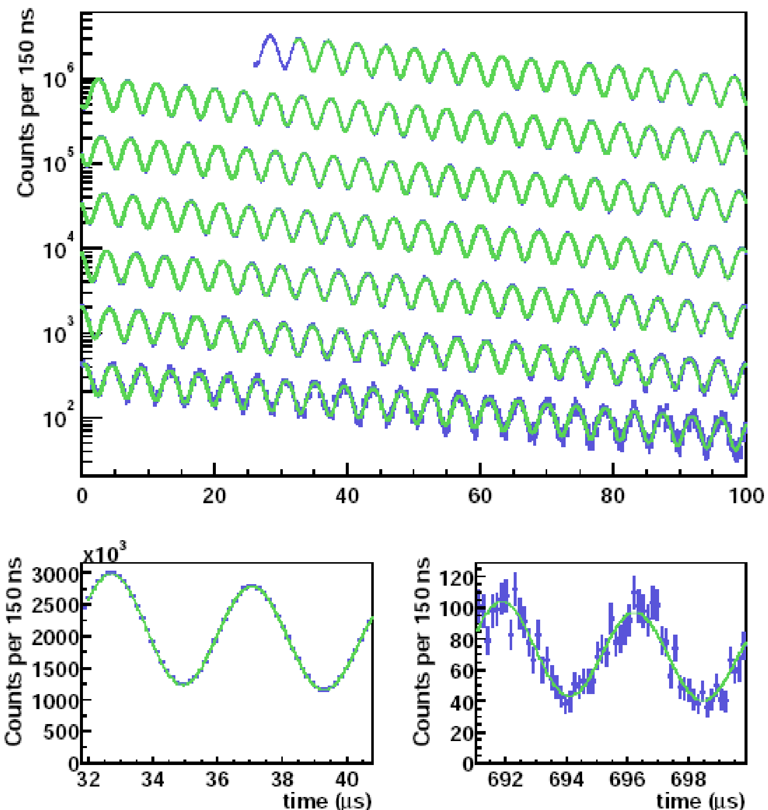
(a) Vacuum chamber cross section

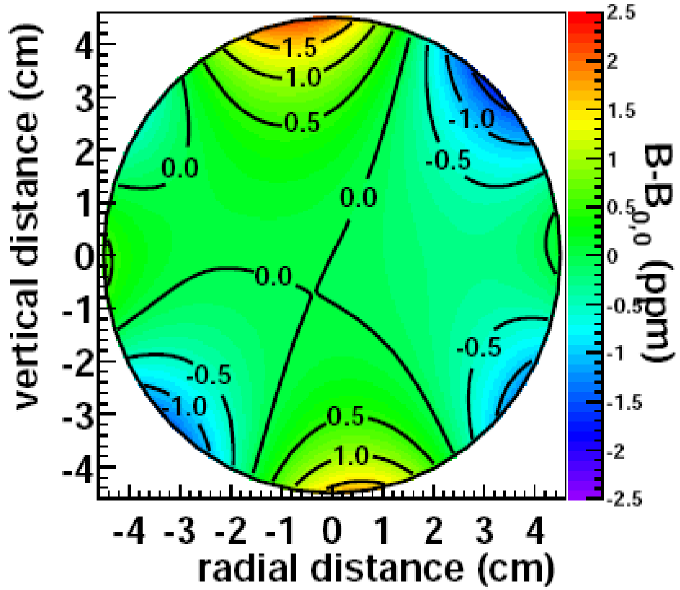
(b) Trolley

- Long list of innovations beyond CERN III
  - Flux in 12 bunches from the AGS
  - Long enough beamline to operate with pion or muon injection
  - Inflector to get muons through the back yoke...allowed muon injection
  - High voltage, fast, non-ferric kickers to shift muon onto orbit in first cycle
  - Thin quadrupoles and scalloped vacuum vessels minimize preshower
  - In situ, field measurements with NMR trolley
  - Continuous NMR monitoring and <0.1 ppm absolute calibration
  - Pb/Scifi calorimeters, hodoscopes, and a traceback wire chambers

Final result from the BNL experiment

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$





	2001 [ppm]	2000 [ppm]
Total Syst Error	0.27	0.39
Statistical Error	0.66	0.62
Total Error	μ^- 0.71	μ^+ 0.73

Stat error dominates!

Combined total error on a_μ 0.54 ppm

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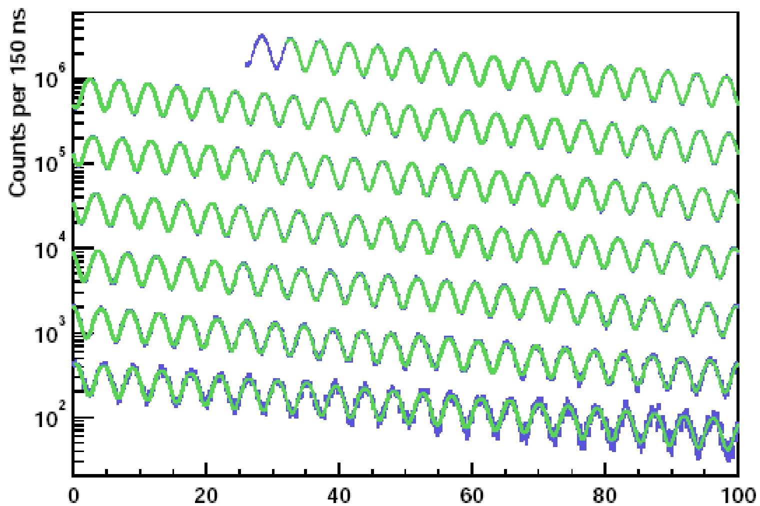
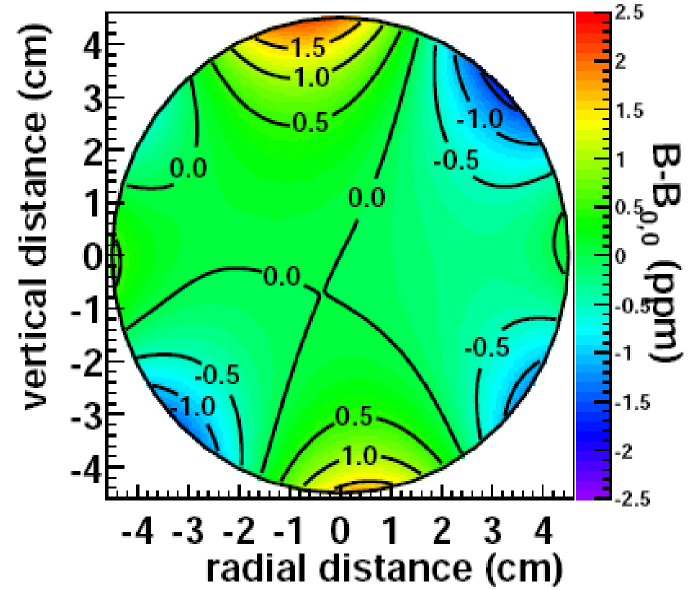
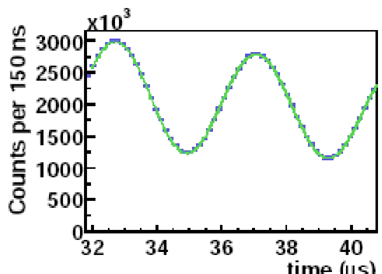
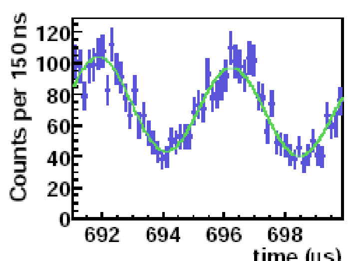








	2001 [ppm]	2000 [ppm]
Total Syst Error	0.27	0.39
Statistical Error	0.66	0.62
Total Error	μ^- 0.71	μ^+ 0.73

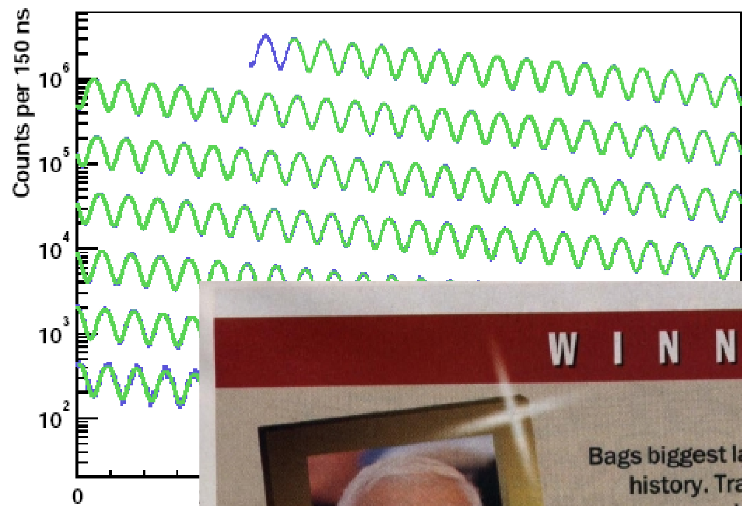
Stat error dominates!

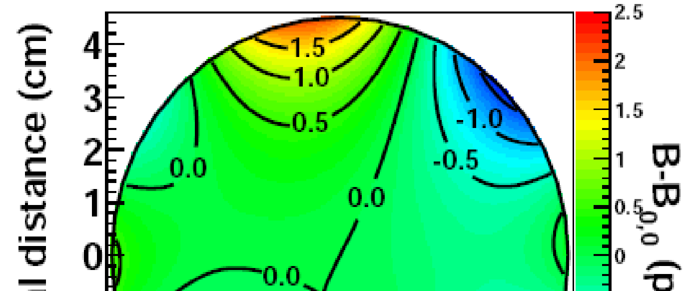
Combined total error on a_μ 0.54 ppm

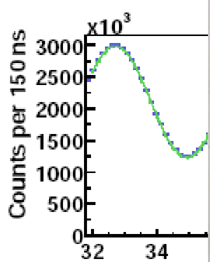
First results published in 2001
indicated a 3σ (exp-thy) difference!

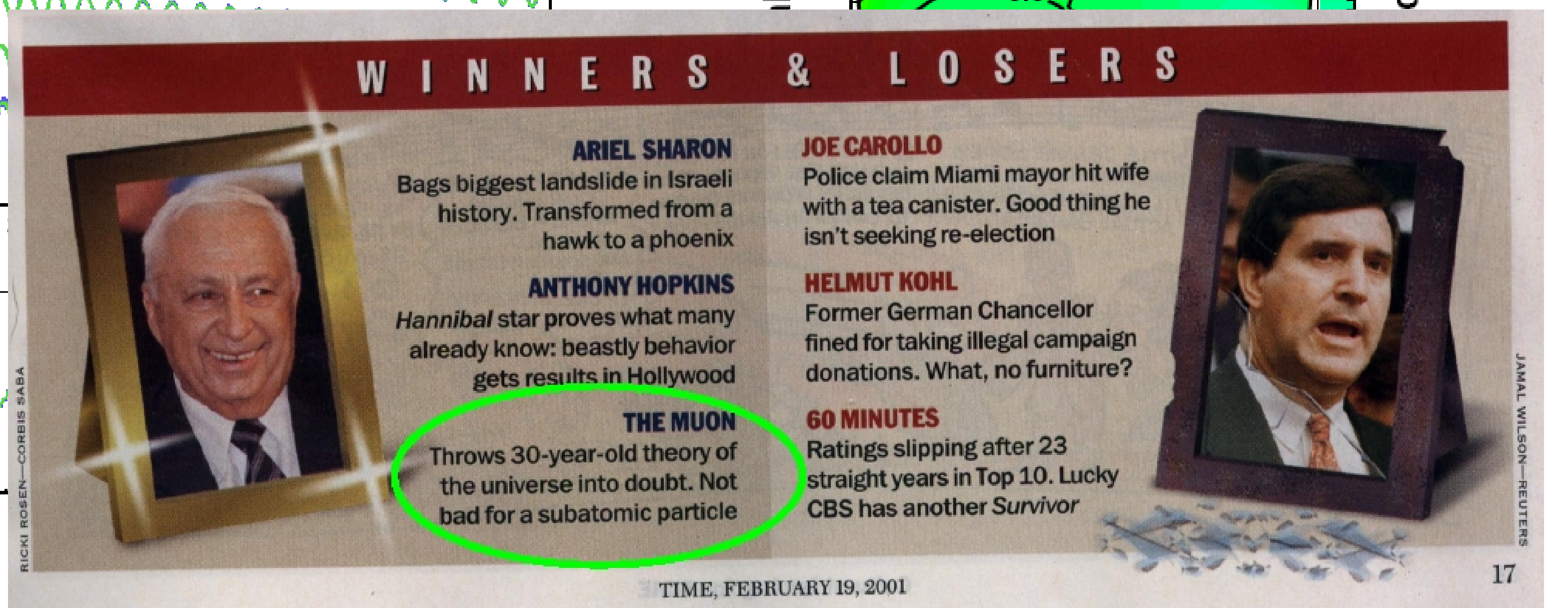
Final result from the BNL experiment

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$









WINNERS & LOSERS

ARIEL SHARON
Bags biggest landslide in Israeli history. Transformed from a hawk to a phoenix

ANTHONY HOPKINS
Hannibal star proves what many already know: beastly behavior gets results in Hollywood

THE MUON
Throws 30-year-old theory of the universe into doubt. Not bad for a subatomic particle

JOE CAROLLO
Police claim Miami mayor hit wife with a tea canister. Good thing he isn't seeking re-election

HELMUT KOHL
Former German Chancellor fined for taking illegal campaign donations. What, no furniture?

60 MINUTES
Ratings slipping after 23 straight years in Top 10. Lucky CBS has another *Survivor*

RICKI ROSEN—CORBIS SABA

JAMAL WILSON—REUTERS

TIME, FEBRUARY 19, 2001

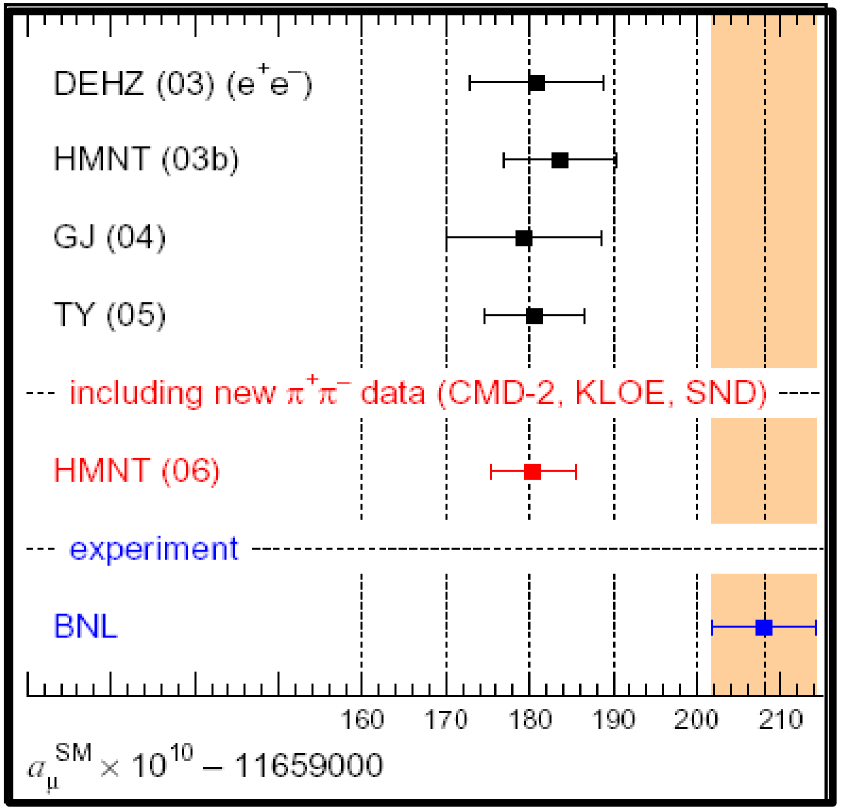
17

Combined total error on a_μ 0.54 ppm

First results published in 2001
indicated a 3σ (exp-thy) difference!

SM evaluations Δa_μ(exp-thy) circca 2008

Theory evaluation stable!



K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

- BNL a_μ(exp) = 116 592 080(63) x 10^{-11}

- Evaluation by De Rafael (arXiv:0809.3025)

CONTRIBUTION	RESULT IN 10^{-11} UNITS
QED (leptons)	$11\ 6584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 908 \pm 39_{\rm exp} \pm 19_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-97.9 \pm 0.9_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 785 \pm 51$

- Leads to a Δa_μ(exp-thy) evaluation, units of a_μ in 10^{-11}
  - Rafael (2008) 295 ± 81 (3.6σ)
- Other modern Δa_μ(exp-thy) evaluations, units of a_μ in 10^{-11}
  - HMNT (2008) 276 ± 81 (3.4σ)
  - DEHZ (2006) 277 ± 84 (3.3σ)
  - Jeger. (2008) 267 ± 96 (2.8σ)

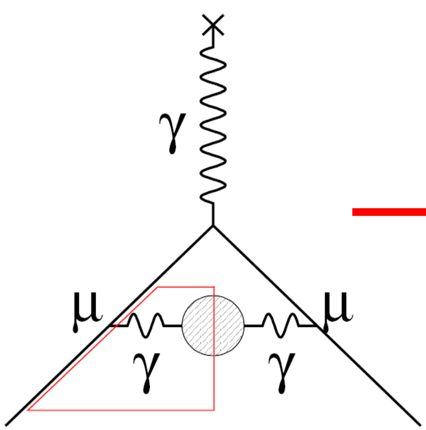
Most difficult part of theory comes from hadronic sector

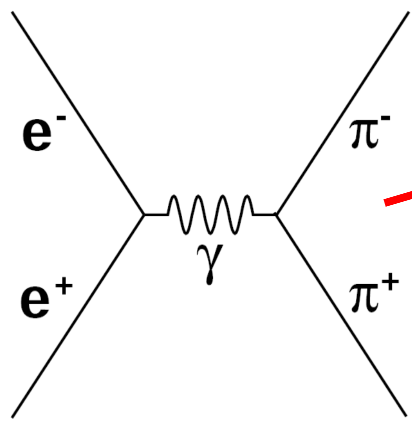
CONTRIBUTION	RESULT IN 10^{-11} UNITS
QED (leptons)	$11\ 6584\ 718.09 \pm 0.14 \pm 0.04_{\alpha}$
HVP(lo)	$6\ 908 \pm 39_{\text{exp}} \pm 19_{\text{rad}} \pm 7_{\text{pQCD}}$
HVP(ho)	$-97.9 \pm 0.9_{\text{exp}} \pm 0.3_{\text{rad}}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 785 \pm 51$

*Courtesy E. De Rafael, arXiv 0809.3025

- Theory error dominated by QCD piece
- Common to divide hadronic loops into 3 categories…
  - a_μ(had,LO) = 6923 ± 42
  - a_μ(had,HO) = -98 ± 1
  - a_μ(had,LBL) = 105 ± 26

Davier *et al.*, EPJ C 71, 1515 (2011)

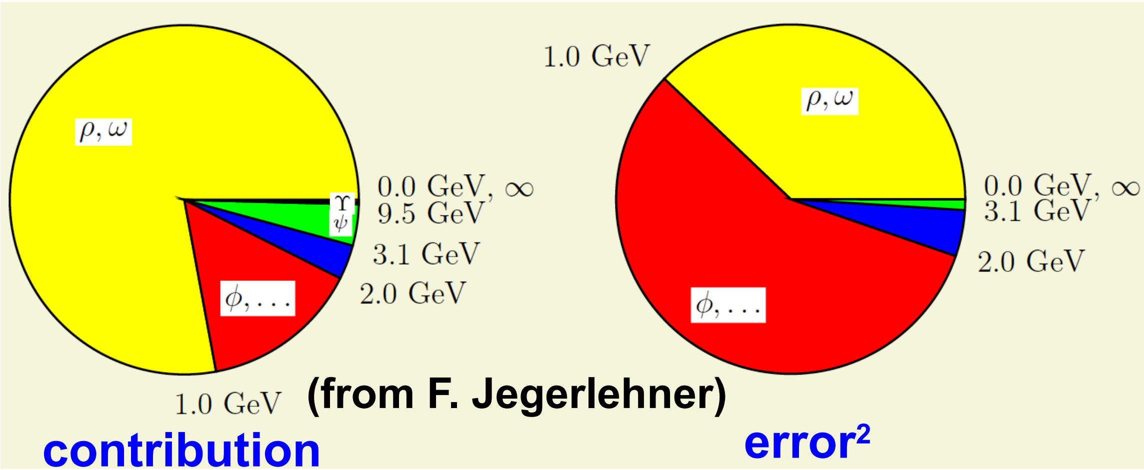




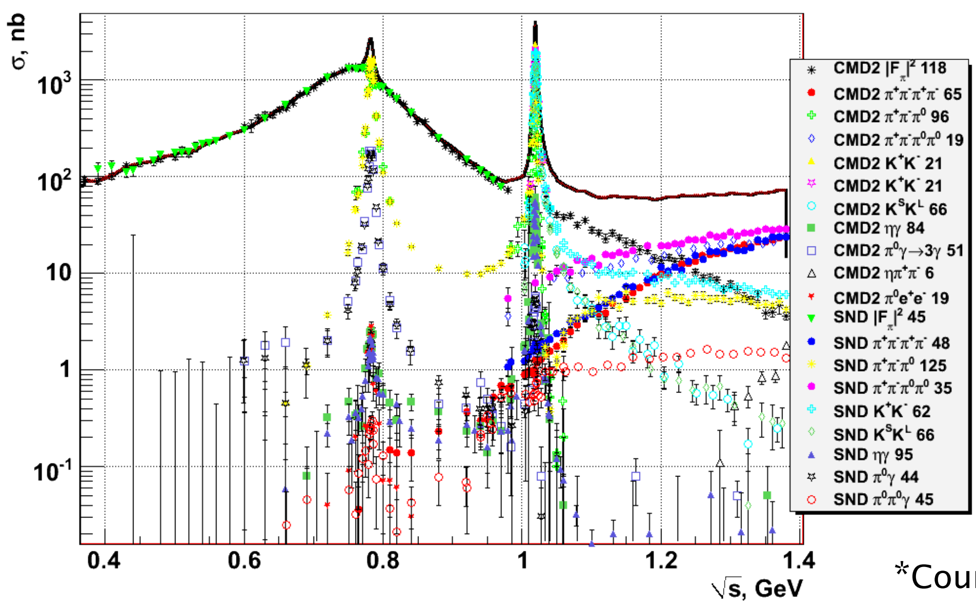
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

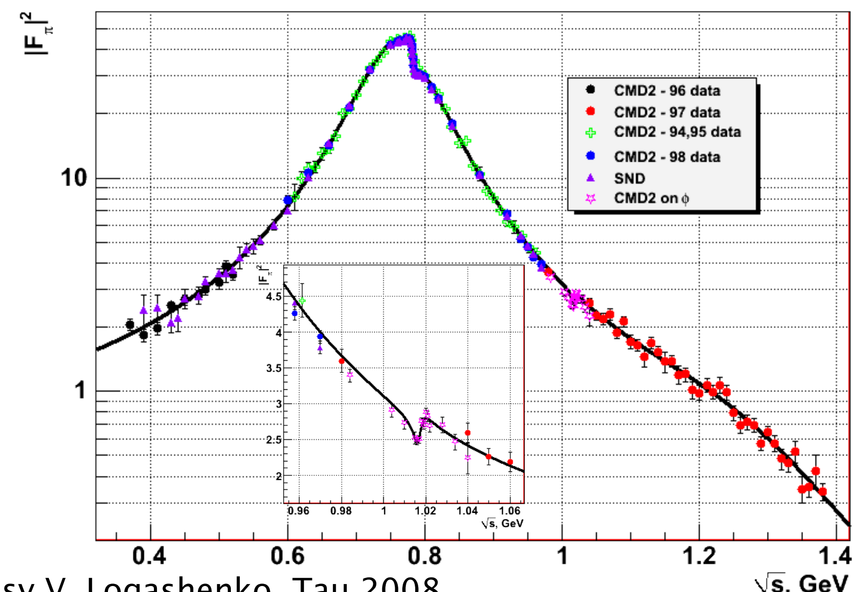
$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Reducing δa_μ(had,LO) requires precision e^+e^- -> hadrons



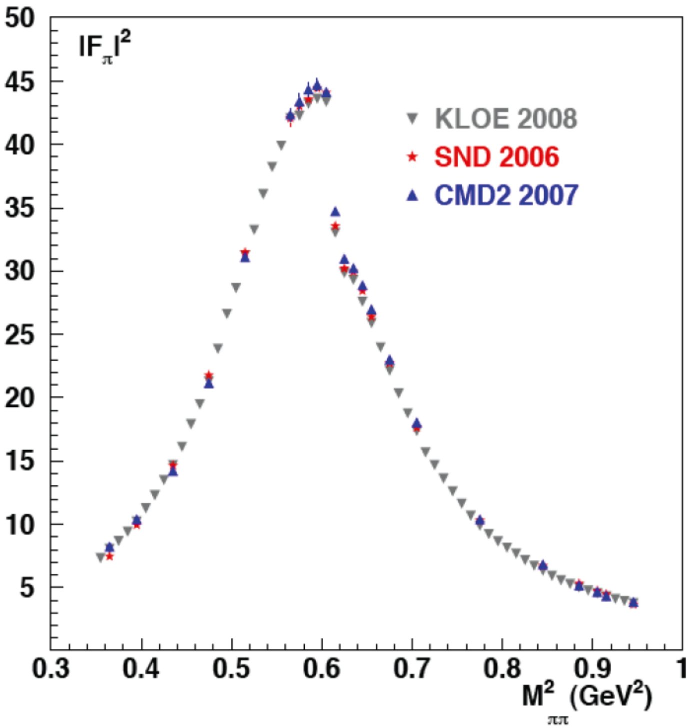
- Experiments have reduced error such that 2π region no longer dominates error
- Data from Novosibirsk (CMD2 and SND)
  - For 2π, ratio $N(2\pi)/N(ee)$, form factor to 1-2%
  - All modes but 2π, luminosity measured using Bhabha scattering

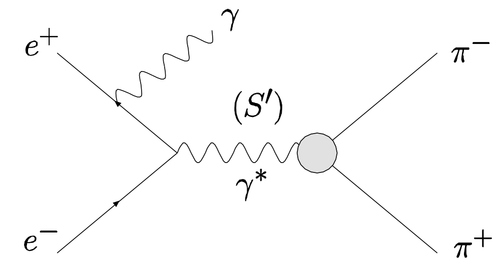


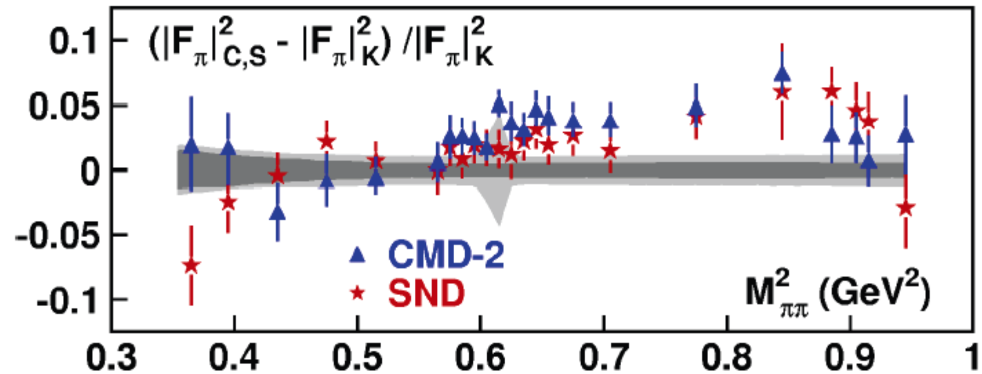


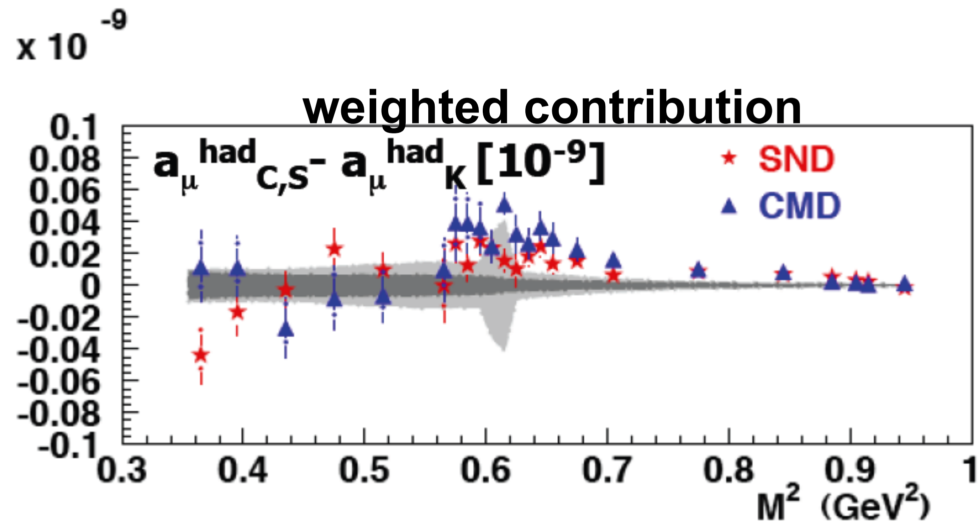
*Courtesy V. Logashenko, Tau 2008

New breakthrough pioneered by KLOE, use of ISR for a_μ





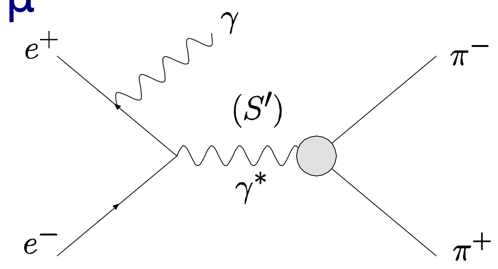




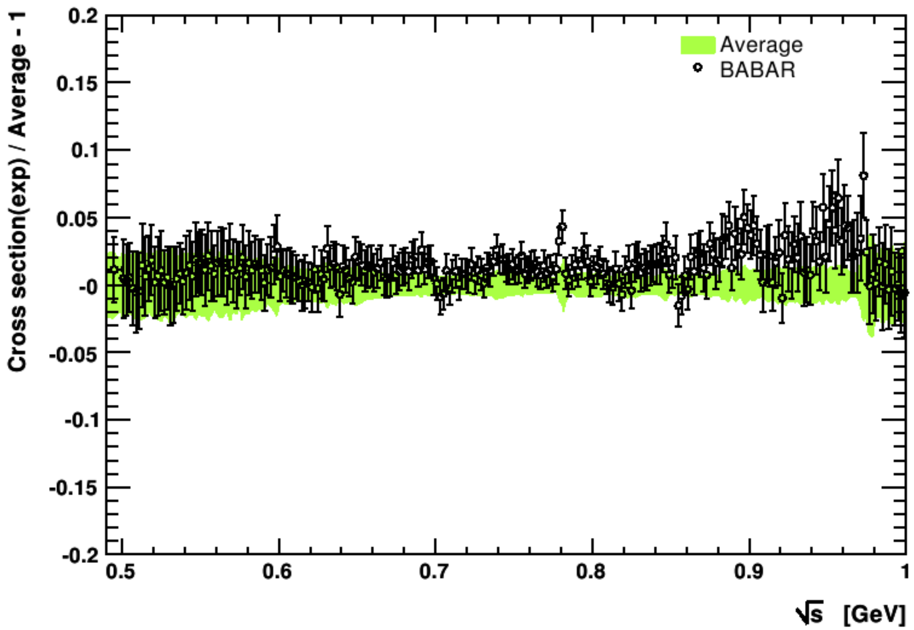
$$\sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

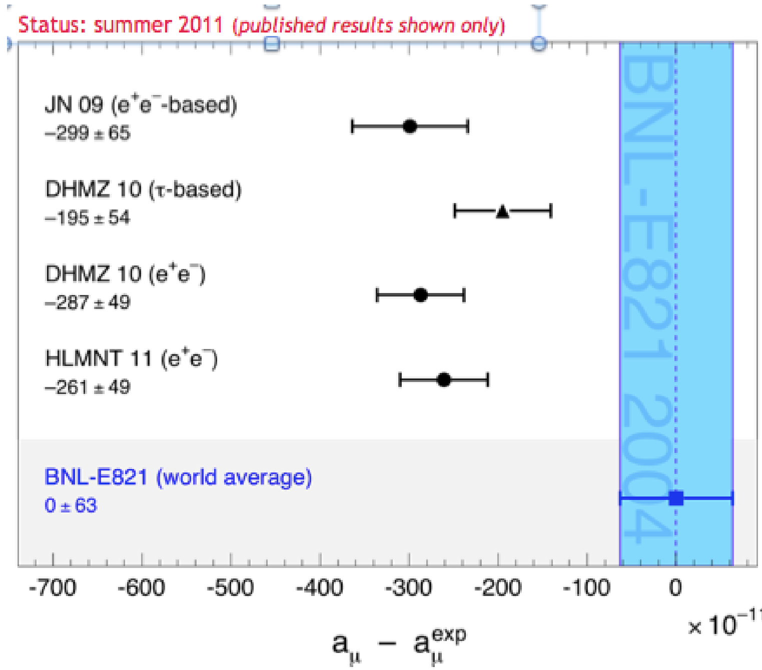
- Unbelievable statistical precision
- KLOE agrees with CMD2 & SND

Results from Babar, also using ISR for a_μ



- Also, statistically precise and only 2nd expt to use ISR
- Some tension (~2σ) with KLOE result
  - Babar reconstructs the ISR photon
  - Babar also measures the denominator of R(s)





Babar has provided a 4th independent vote of confidence in theory...good, need that to extract new physics

Putting all the pieces together, circa 2011

	Value ($\times 10^{-11}$) units
QED	$116\,584\,718.09 \pm 0.14 \pm 0.04_{\alpha}$
HVP(lo)	$6\,955 \pm 40_{\mathrm{exp}} \pm 7_{\mathrm{pQCD}}$
HVP(ho)	$-97.9 \pm 0.8_{\mathrm{exp}} \pm 0.3_{\mathrm{rad}}$
HLxL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,834 \pm 41_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\mathrm{other}}$ $(\pm 49_{\mathrm{tot}} = 0.42_{\mathrm{ppm}})$

$$a_{\mu}^{exp} = 116\,592\,089(63) \times 10^{-11} \; (0.54\,\mathrm{ppm})$$

$$\Delta a_{\mu} \equiv a_{\mu}^{exp} - a_{\mu}^{SM} = (255 \pm 80) \times 10^{-11}$$

So the 3σ discrepancy remains...outside of dark matter and ν-oscillations one of the most intriguing evidence for BSM physics

This 3σ difference particularly relevant in LHC era..

- Imagine SUSY is proven to be reality...

  But which model is correct?

  - Huge resolving power between various scenarios
  - g-2 primarily sensitive to sleptons and charginos, LHC squarks and gluinos

- Kaluza-Klein states or MSSM?

  $\Delta a_\mu(\mathrm{UED}) = -13 \times 10^{-11}$

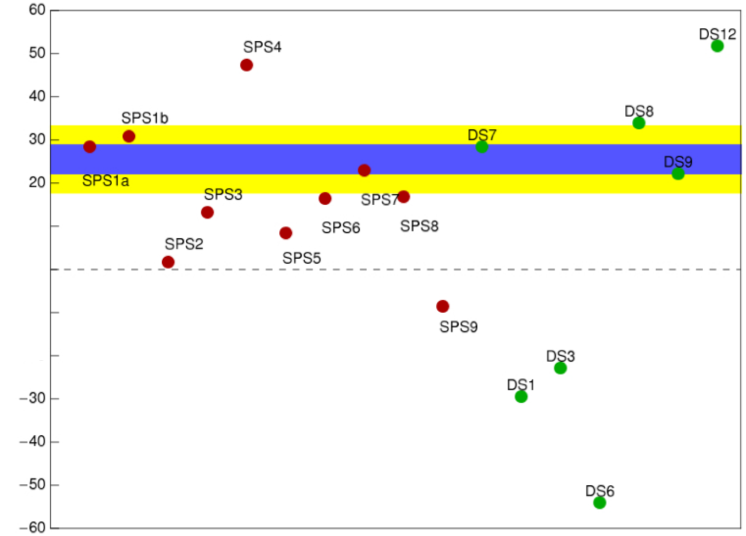
  $\Delta a_\mu(\mathrm{MSSM}) = 298 \times 10^{-11}$

- $\tan\beta$ hard at LHC, g-2 much stronger

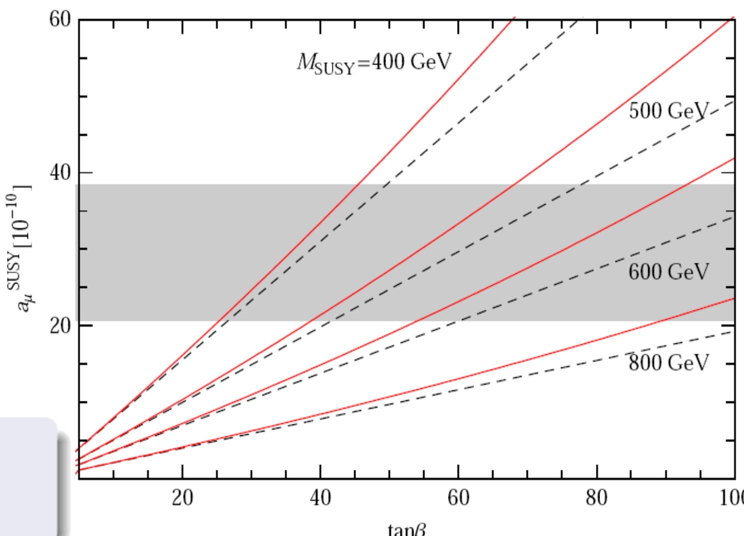
- Lots of other models (besides SUSY) continually confronted by g-2...general

vision: test universality of $\tan\beta$, like for $\cos\theta_W = \frac{M_W}{M_Z}$ in the SM:

$$(t_\beta)^{a_\mu} = (t_\beta)^{\mathrm{LHC,masses}} = (t_\beta)^H = (t_\beta)^b?$$

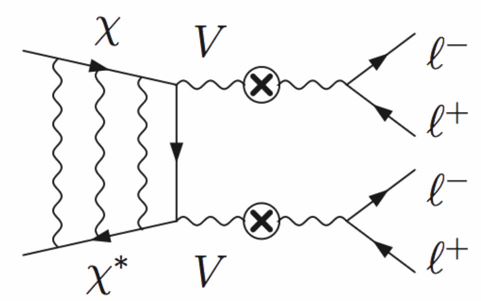


SPS benchmark points LHC Inverse Problem (300fb^{-1})



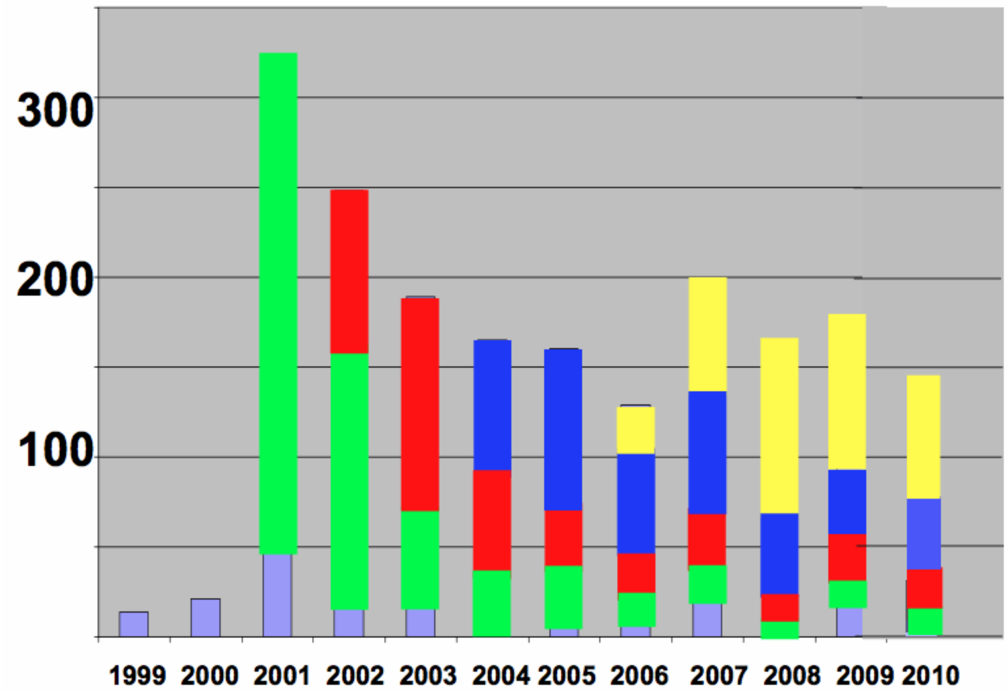
Marchetti, Mertens, Nierste, Stockinger (0808.1530)

This 3σ difference particularly relevant in LHC era..

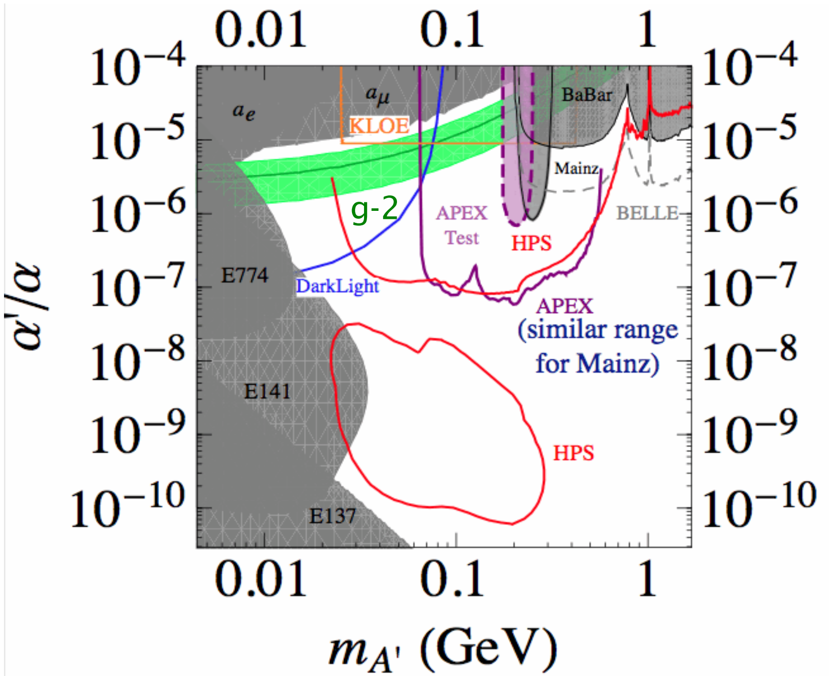


Arkani-Hamed, Finkbeiner, Slatyer, Weiner, Pospelov, Ritz

Muon g-2 Citations

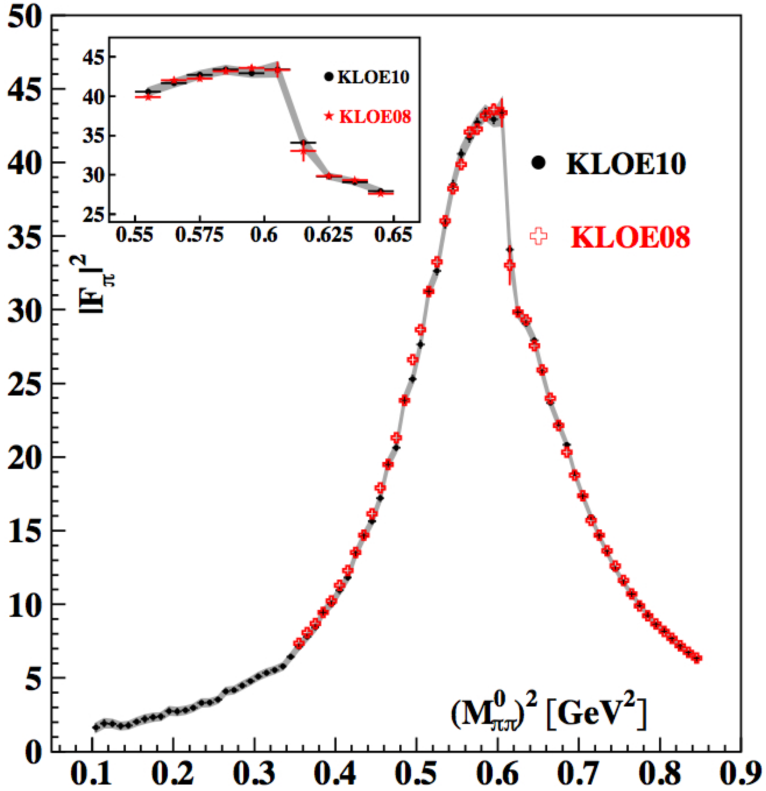


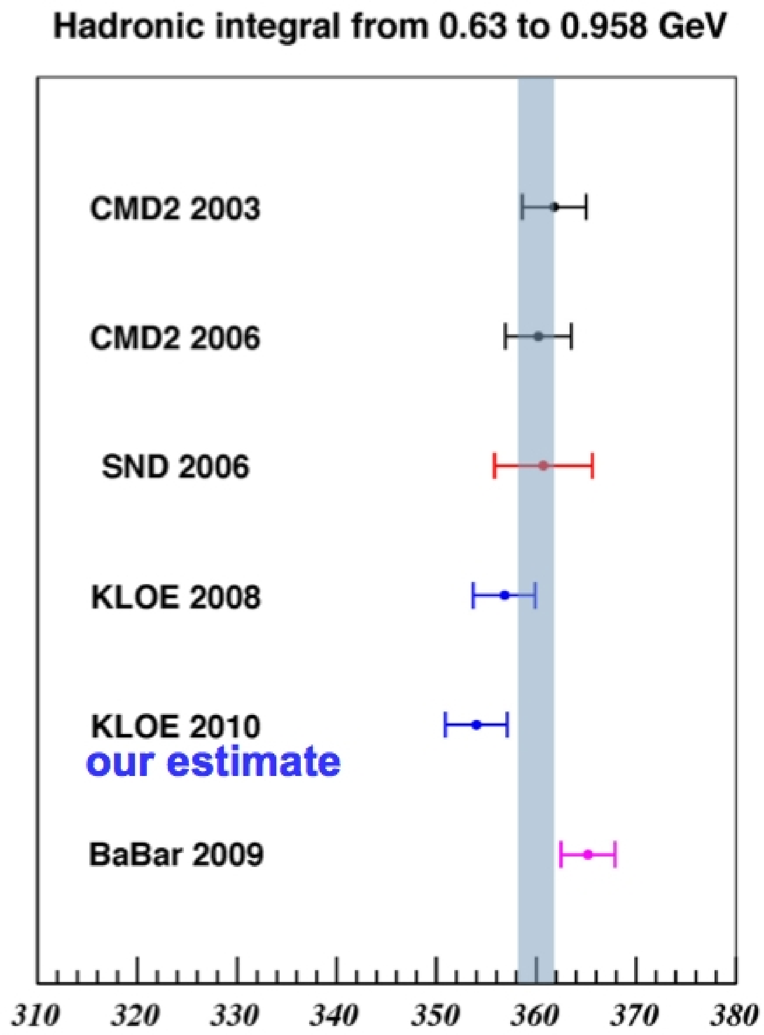
*100 so far in 2011



Sensitivity to new U(1) gauge coupling to dark sector

Future improvements (are already here)



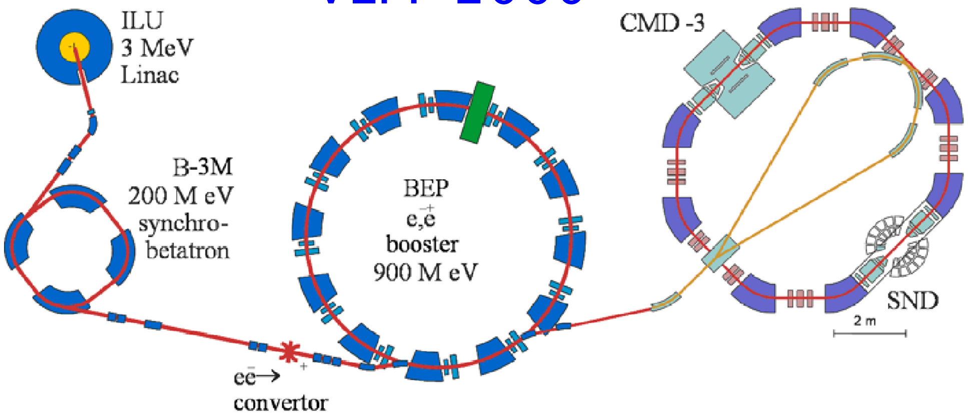


chi2/dof=8.8/5

- Independent, large-angle data sample, ISR photon reconstructed
- KLOE10 in good agreement with KLOE08, still some tension with Babar09

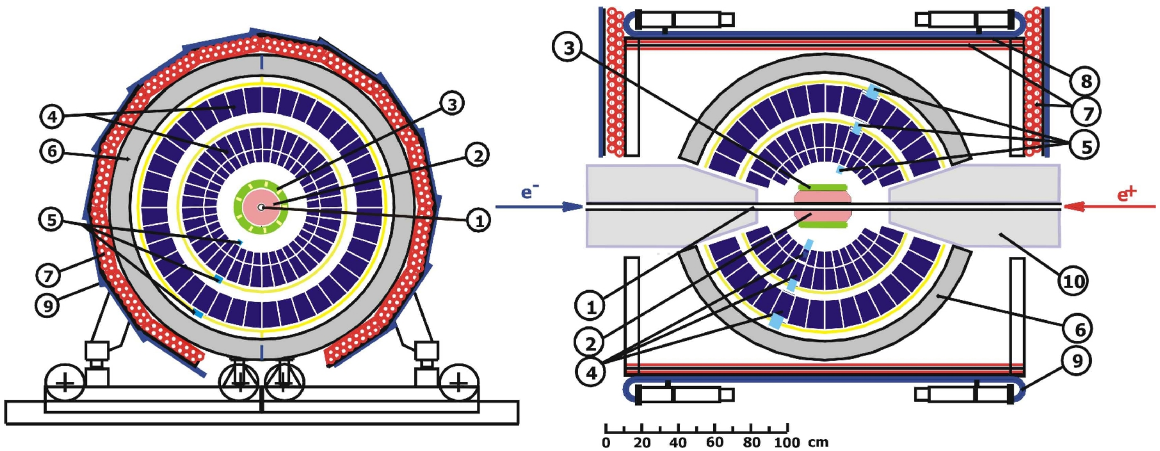
New facility VEPP-2000 and upgraded detectors

VEPP-2000

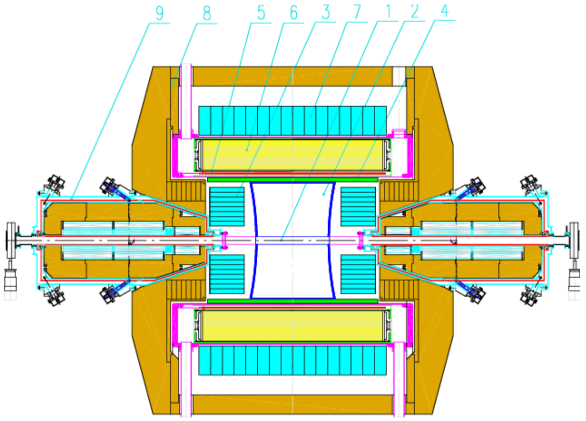


- Lots of machine and detector upgrades in Novosibirsk
  - Factor of 10-100 in stats, > 10 from luminosity alone
  - Energy extend range up to 2 GeV
- Experiments started in 2010!!!
- Not to mention more ISR results from KLOE & Babar, maybe Belle

SND2000



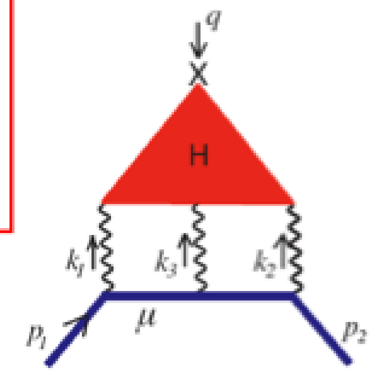
CMD3



Hadronic Light–by–Light Scattering Contribution to the Muon Anomalous Magnetic Moment

arXiv:0901.0306v1, and in Lepton Dipole Moments (World Scientific Press 2010)

Joaquim Prades[a], Eduardo de Rafael[b] and Arkady Vainshtein[c]



$$a^{HLbL}(\pi,\eta,\eta') = (114 \pm 13) \times 10^{-11}$$

$$a^{HLbL}(\text{scalars}) = -(7 \pm 7) \times 10^{-11}$$

$$a^{HLbL}(\pi\,\text{dressed loop}) = -(19 \pm 19) \times 10^{-11}$$

$$a^{HLbL}(\text{pseudovectors}) = (15 \pm 10) \times 10^{-11}$$

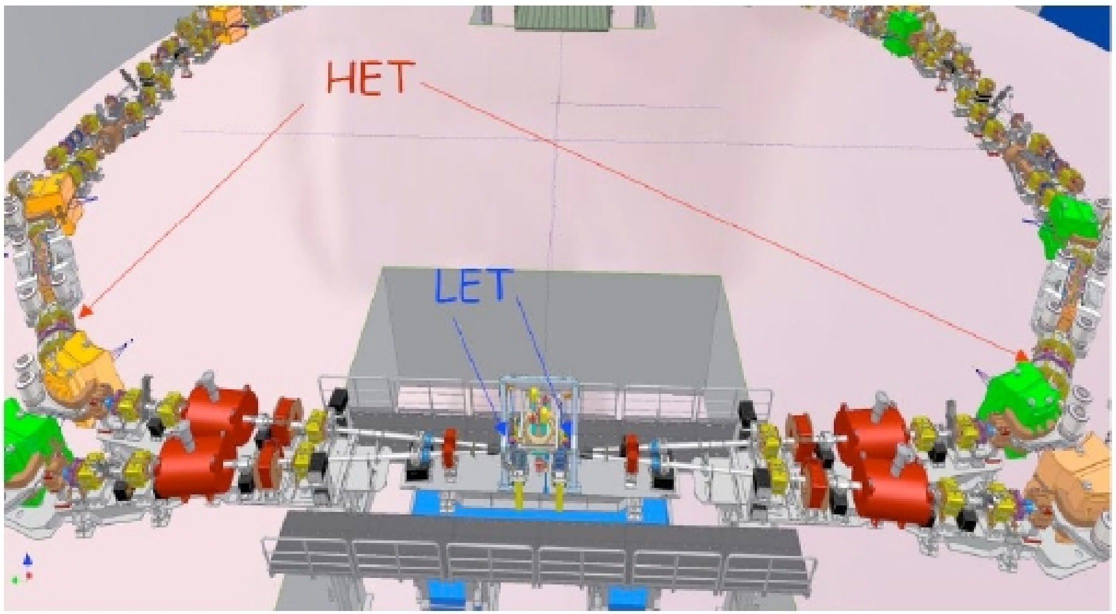
Dynamical models with QCD behavior

$$a_\mu^{\text{HLBL}} = 105\ (26) \times 10^{-11}$$

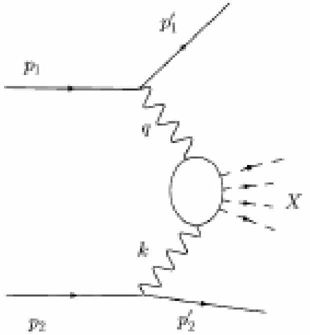
With Δa_μ = 255 x 10^{-11}, if HLBL is the source of the difference with SM, it would need to increase by 10 σ

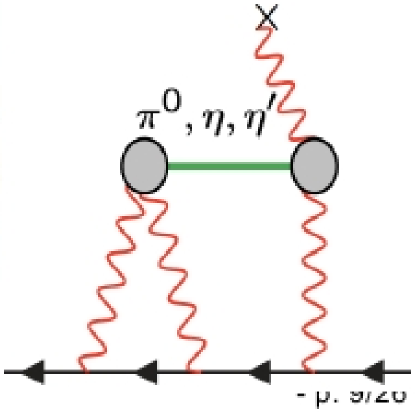
KLOE to measure $\gamma^*\gamma^* \to$ *hadrons* to constrain HLBL

- Constrain the off-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL



The New Muon (g-2) Collaboration, Fermilab PAC – 13 November 2009

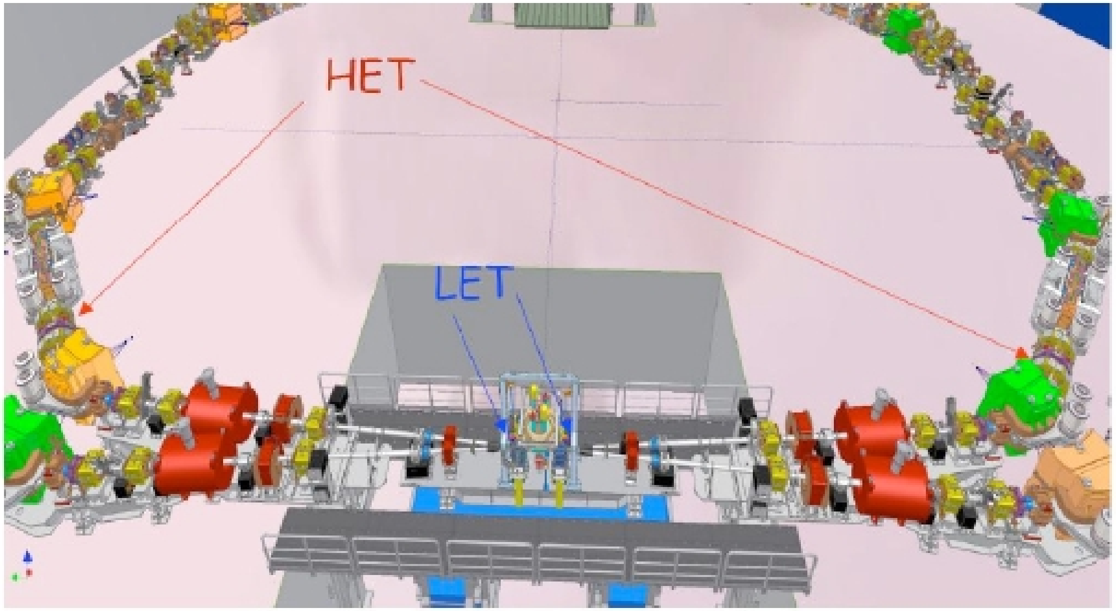


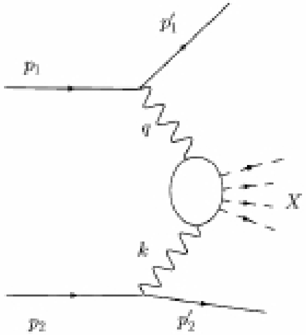


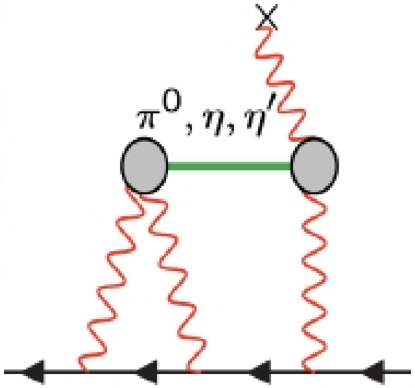
First time we will have an experimental constraint on HLBL (~60% of it)

KLOE to measure $\gamma^*\gamma^* \to$ *hadrons* to constrain HLBL

- Constrain the off-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL







The New Muon (g-2) Collaboration, Fermilab PAC – 13 November 2009

KLOE also requesting \$20M to upgrade machine to 2.5 GeV and have an ISR check of Novosibirsk

We are proposing to move the muon g-2 apparatus to FNAL

- Why?
  - Because the experiment ended statistics-limited...magic γ method still has potential
  - Because for nearly 10 years theory has been stable and indicating a 3σ diff with the experiment
  - Because we all are hoping for new information to come from direct production at the LHC, and muon g-2 will have enormous resolving power for new physics

- How much better?
  - Theory error is already 80% of experimental and could come down 40% in foreseeable future
  - Need at least a factor of 2 to match theory, but would like to get a factor 4 to be safely ahead
  - Factor of 4-5 will also start to hit the limitations of the experiment

With realistic assumption on systematic errors, we need a factor of 21 in statistics for total exp error to be quartered.

We are proposing to move the muon g-2 apparatus to FNAL

- Why?
  - Because the experiment ended statistics-limited...magic γ method still has potential
  - Because for nearly 10 years theory has been stable and indicating a 3σ diff with the experiment
  - Because we all are hoping for new information to come from direct production at the LHC, and muon g-2 will have enormous resolving power for new physics

Where would we be with these assumptions on experimental and theoretical errors?

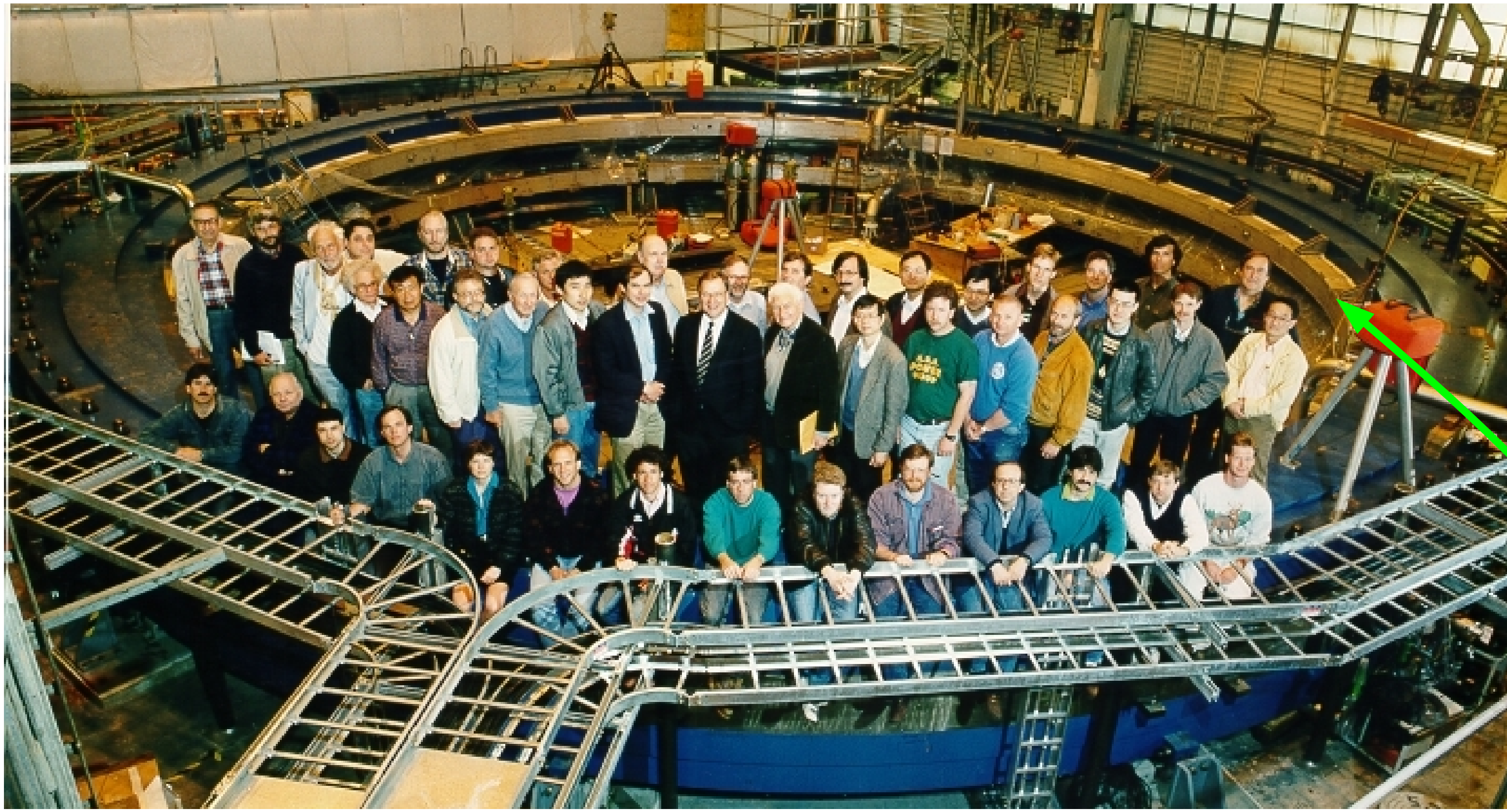
30

16

$$a_\mu^{SM} = 116\,591\,834(49) \times 10^{-11} \ (0.42\,\text{ppm})$$
$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11} \ (0.54\,\text{ppm})$$
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (255 \pm 80) \times 10^{-11}$$

If the central value remain unchanged the significance of the current discrepancy would be 7.5σ!
(5σ with no theory improvements)

One problem...the ring is in Brookhaven!!!

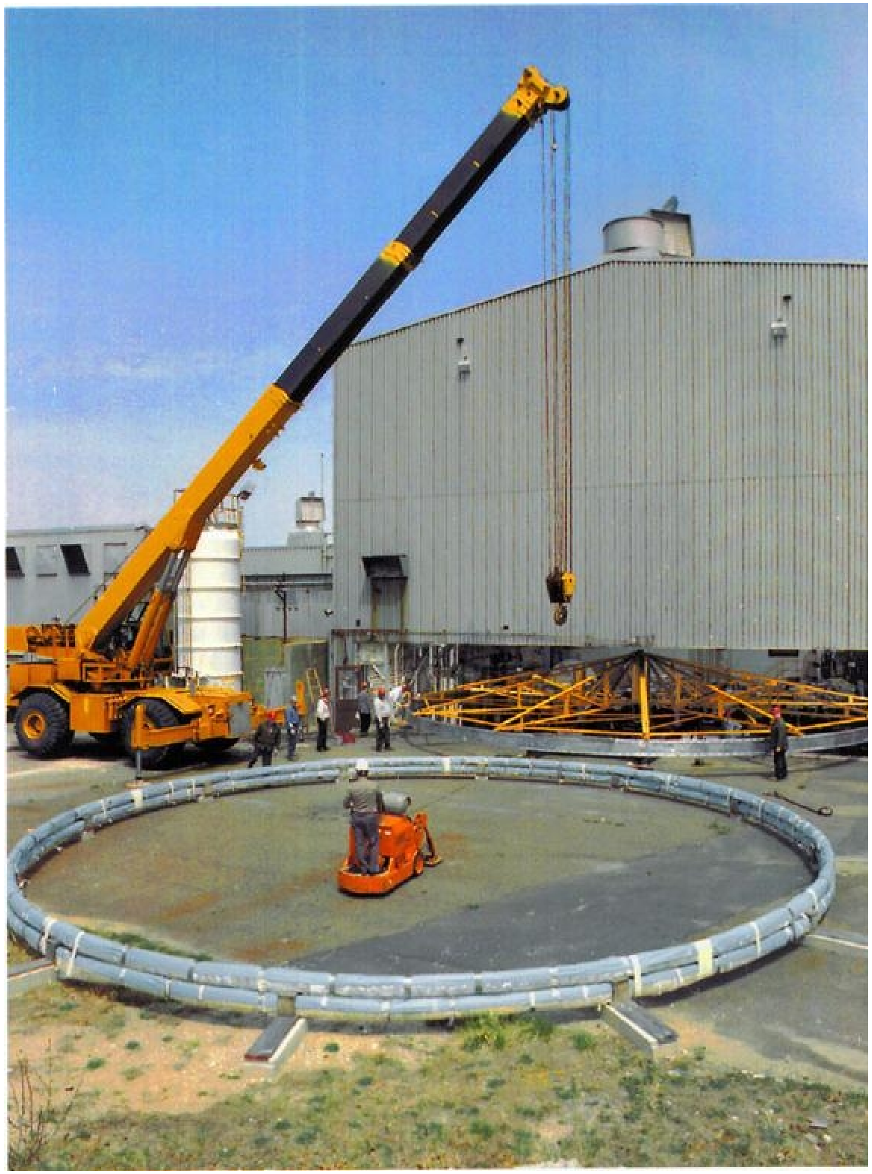


- Ring built in 12 sections and can be disassembled. Moving 600 tons of steel in yoke and subsytems 'easy' part
- Monolithic 14 m diameter cryostats with superconducting coils inside are a little harder

No problem

- Transport coils to and from barge via Sikorsky S64 aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland or on barge

Load not an issue and coils moved before



- Erickson Aircrane: Sikorsky S-64F specs
  - Rotor diameter 22.7 meters... compare to 14.5 meter diameter coils
  - Max hook weight 12.5 tons...compare to max coil weight of 8 tons
- Craned in past with lifting fixture shown
- Total in helicopter opearations <$380k

No 1994 UFO shot down on Long Island

"Nope, no UFOs at Brookhaven",
Symmetry, July 2009

No 1994 UFO shot down on Long Island

"Nope, no UFOs at Brookhaven", Symmetry, July 2009

No 1994 UFO shot down on Long Island...or was there?

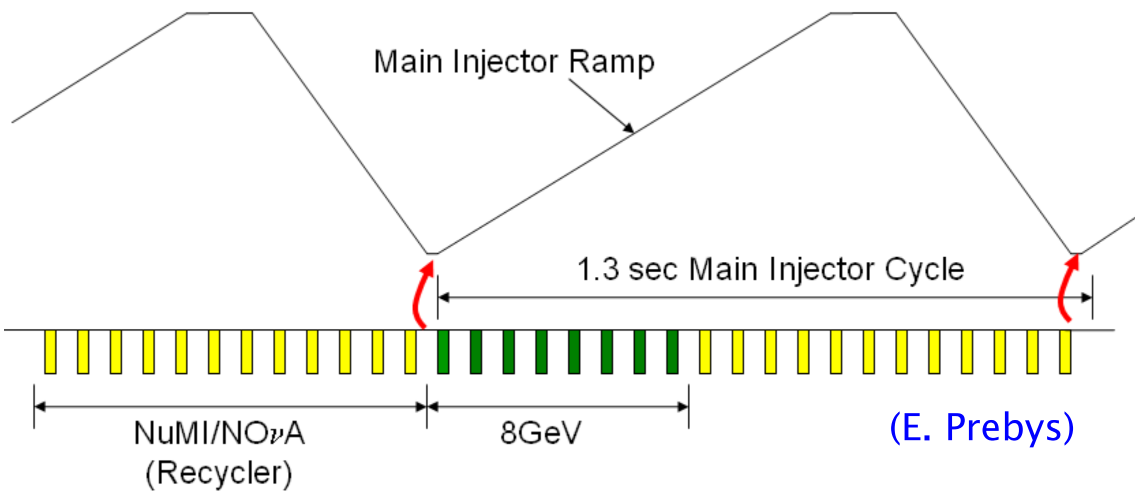
"Nope, no UFOs at Brookhaven", Symmetry, July 2009

FNAL Plan--Booster

(Ankenbrandt, Popovic, Syphers)

- 8 batches available in NOvA era, plan to use 6
  - 6 batches/1.3s = 4.6 Hz
- MiniBooNE experience 1 HZ -> 1.1e20 POT/yr
- Potentially 5e20 POT/yr available, but heavily depends on controlling losses in Booster
- For planning purposes, assume 4e20 POT/yr

NOνA Time Line

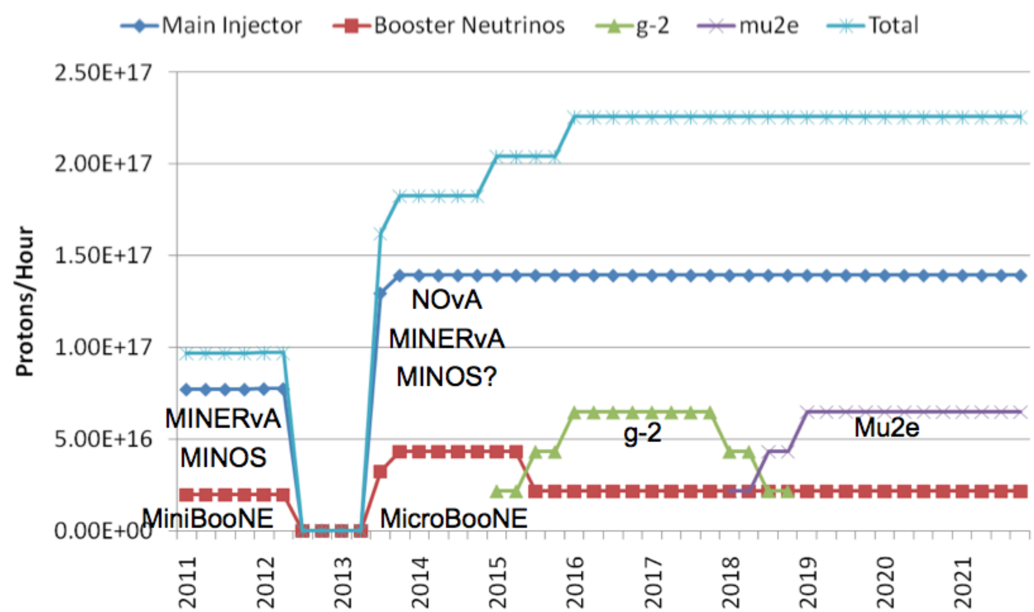


(E. Prebys)

FNAL Plan--Booster

- For planning purposes, assume 4e20 POT/yr
  - Compatible with other 8 GeV demands

Experiment	Total Beam Request	Data Start
MicroBooNE	6.7×10^{20} POT	2013-14
$g-2$	4.0×10^{20} POT	2015-16
Mu2e	7.2×10^{20} POT	2018-19

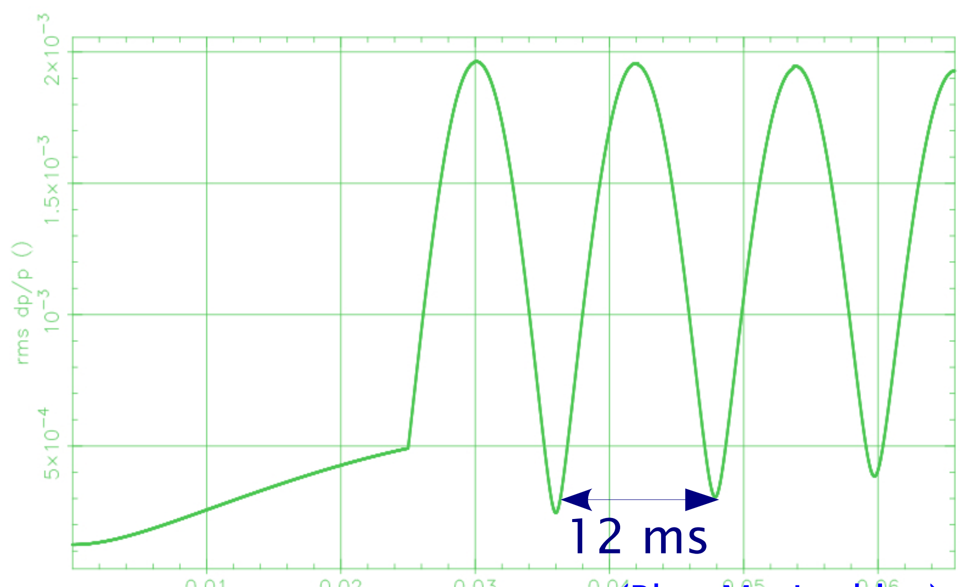


FNAL Plan--Booster to Recycler

- Use same transfer into the Recycler as NOvA

FNAL Plan--Recycler

- To control rate-dependent systematics, need to rebunch each Booster batch into 4 bunches in the Recycler, 400 ns spacing
    - implies average rate of ~18 Hz into exp., compared to 4.5 Hz at BNL E821
- Need to move 2.5 and 5.0 MHz RF systems from MI to Recycler, possibly need to increase voltage by 10-30%
- Extract bunch every 8-12 ms

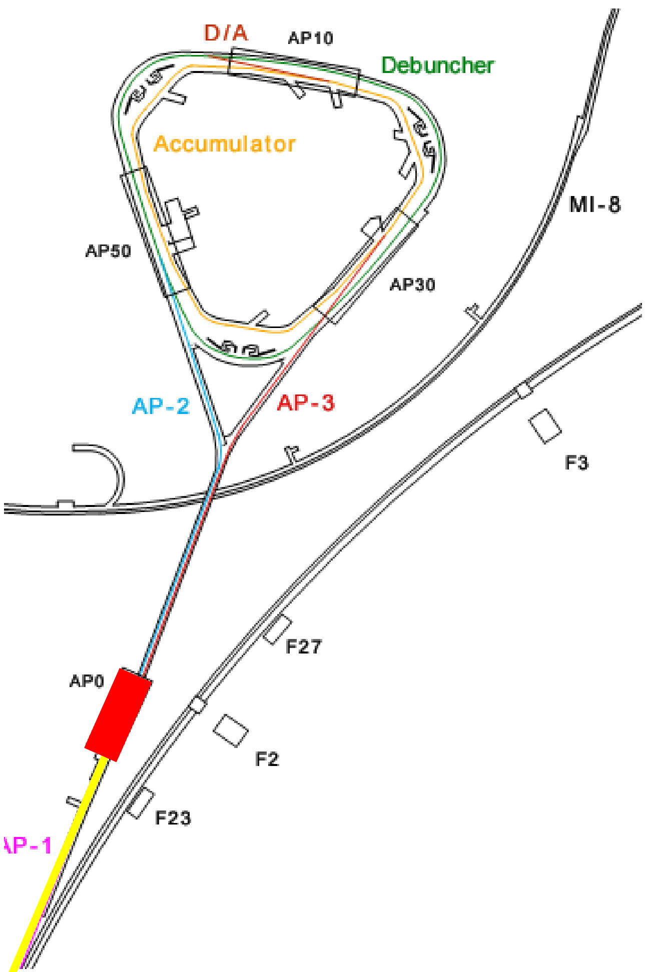


(Bhat,MacLachlan)

FNAL Plan--Extraction to AP1

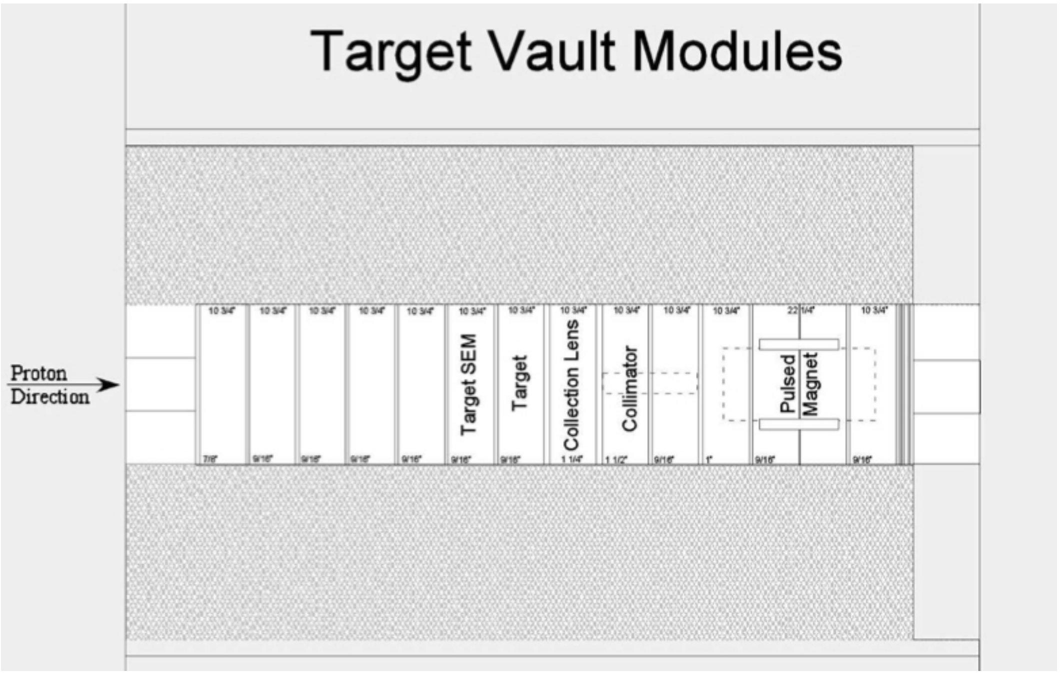
- Very similar to NOvA injection line
- Connects Recycler to P1line --> P2 --> AP1
- Need a kicker to eject bunch every 12 ms
  - Average rate of 18 Hz
  - Rise time 180 ns, flat top 50 ns, back down in 5 μs, ready to kick again in 12 ms
- Reduce losses in P1/P2 to handle 25 MW, 8 GeV beam

FNAL Plan--AP0 Target Station

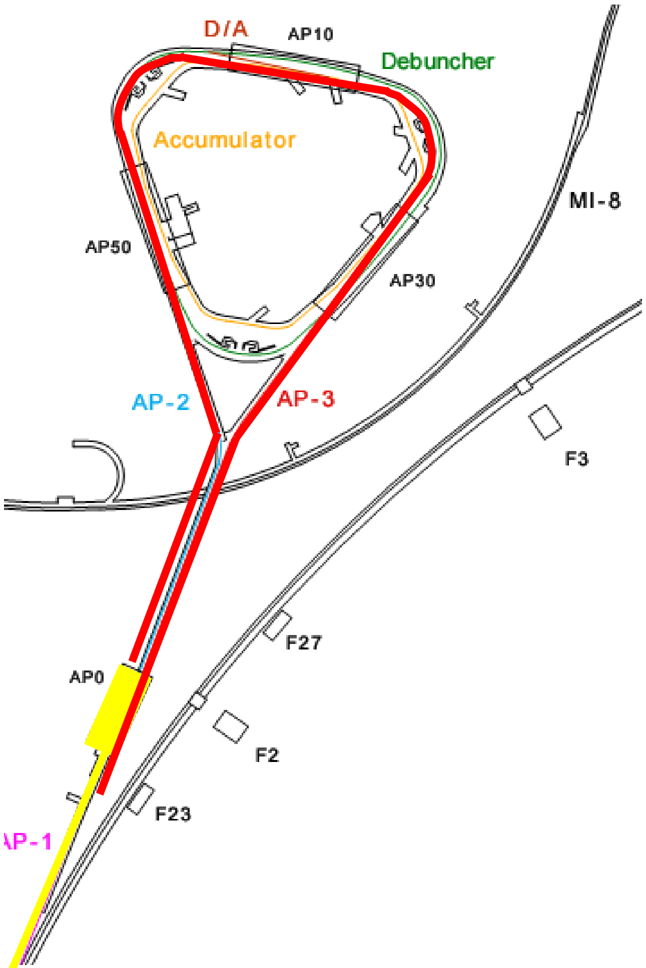


- Plan A: Use conventional rad-hard quads
  - Solution used in BNL E821
- Plan B: Reuse current target & Li lens
  - Have to evaluate if Li lens can operate at higher rate with reduced current
- Also looking at a multi-turn, DC PMAG design

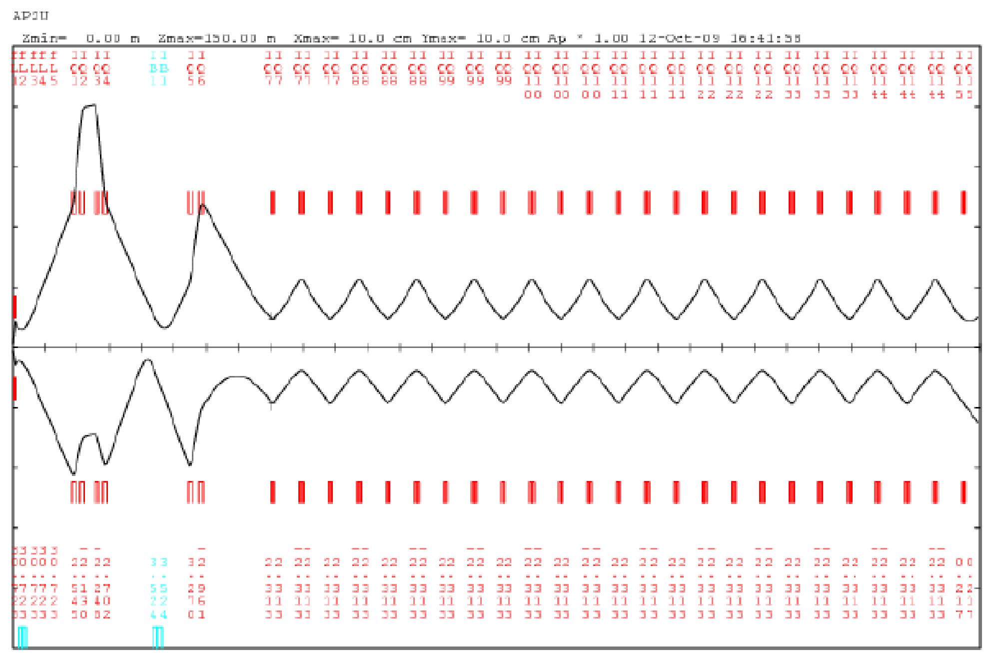
(Huhr, Leveling, Mokhov, Morgan, Nagaslaev, Striganov, Werkama, Wolff)



FNAL Plan--Pion decay line



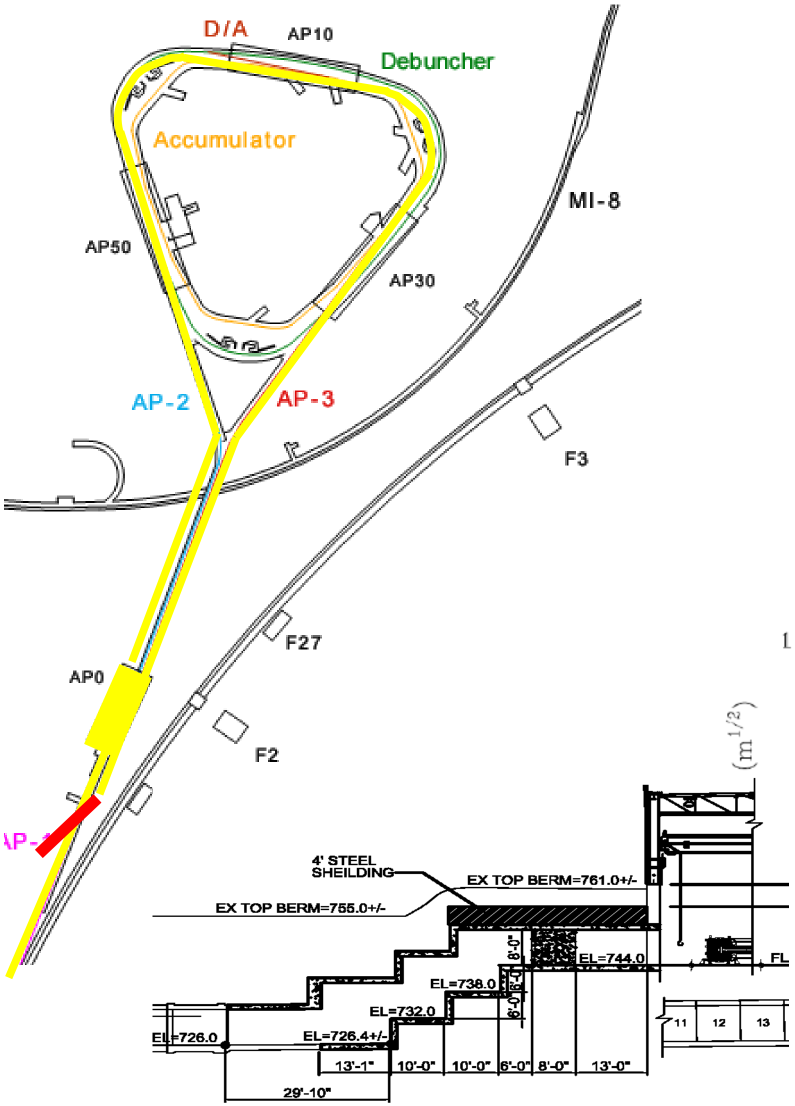
- Critical to the experiment is an 800 m or longer decay line ($\pi^+ \text{-->} \mu^+$)
- Plan to use AP2 --> Debuncher --> AP3
  - New connection DEB-->AP3
  - Denser quad spacing in AP2/AP3

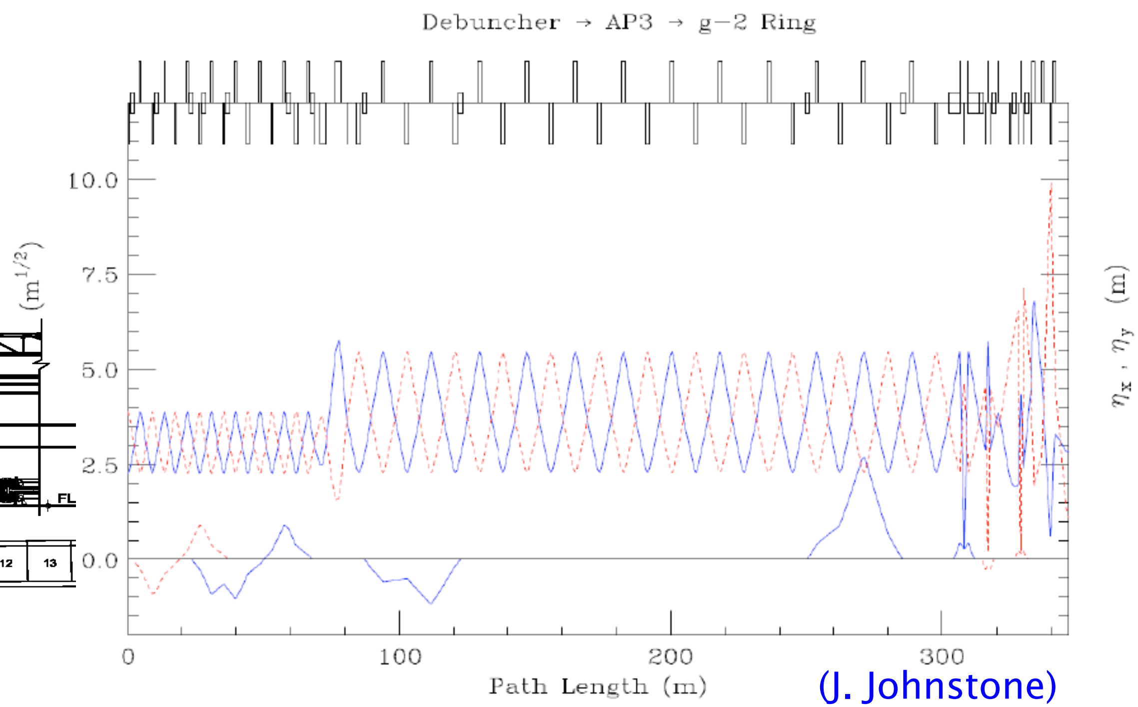


(J. Johnstone)

FNAL Plan--New tunnel to surface building

- Need to bring beam up to surface building
- Complicated optics
  - Horizontal and vertical bends keeping dispersion controlled
  - Match final optics into ring

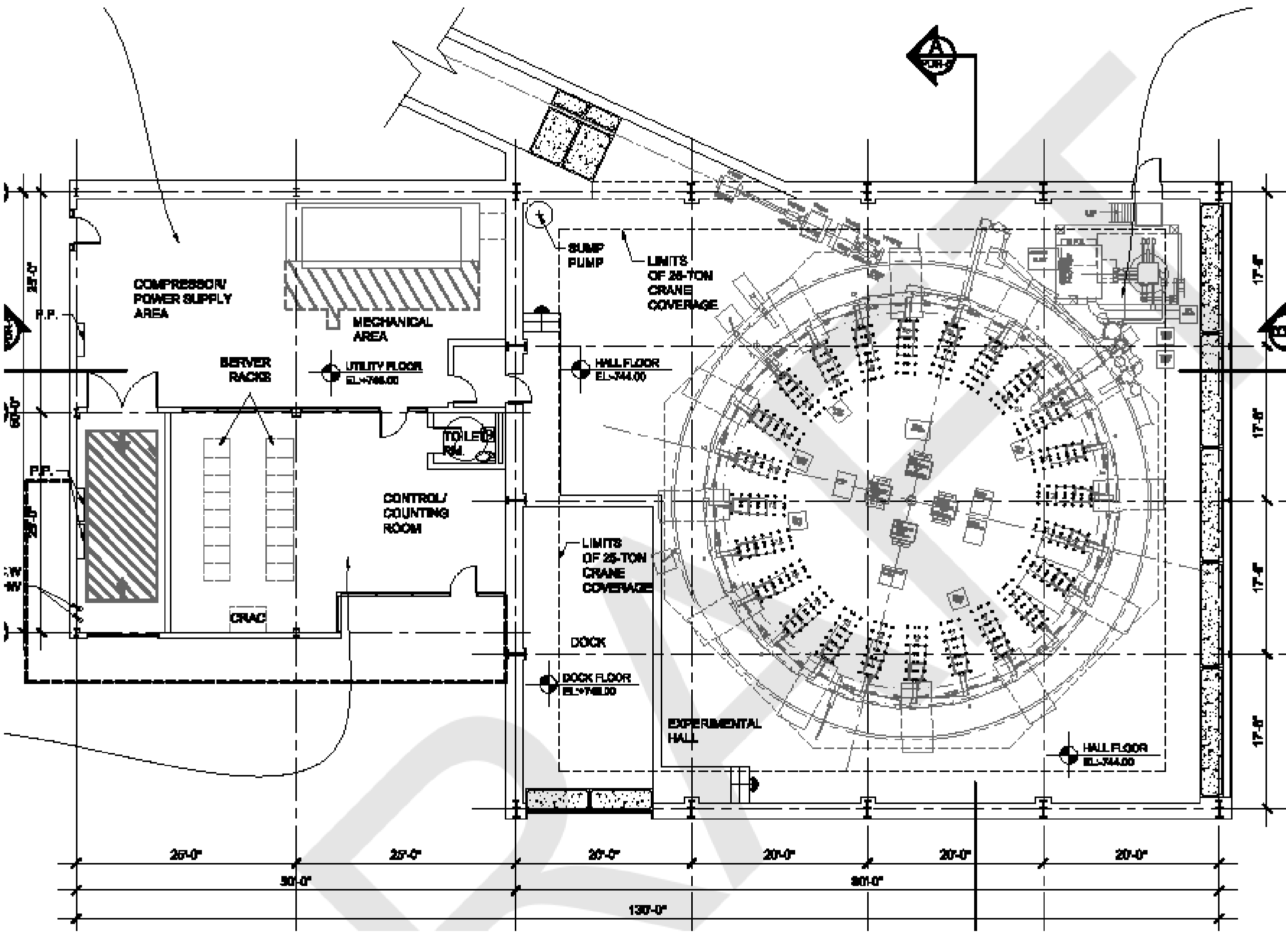




(J. Johnstone)

Muon beam delivered to new building

Overhead view of new building design

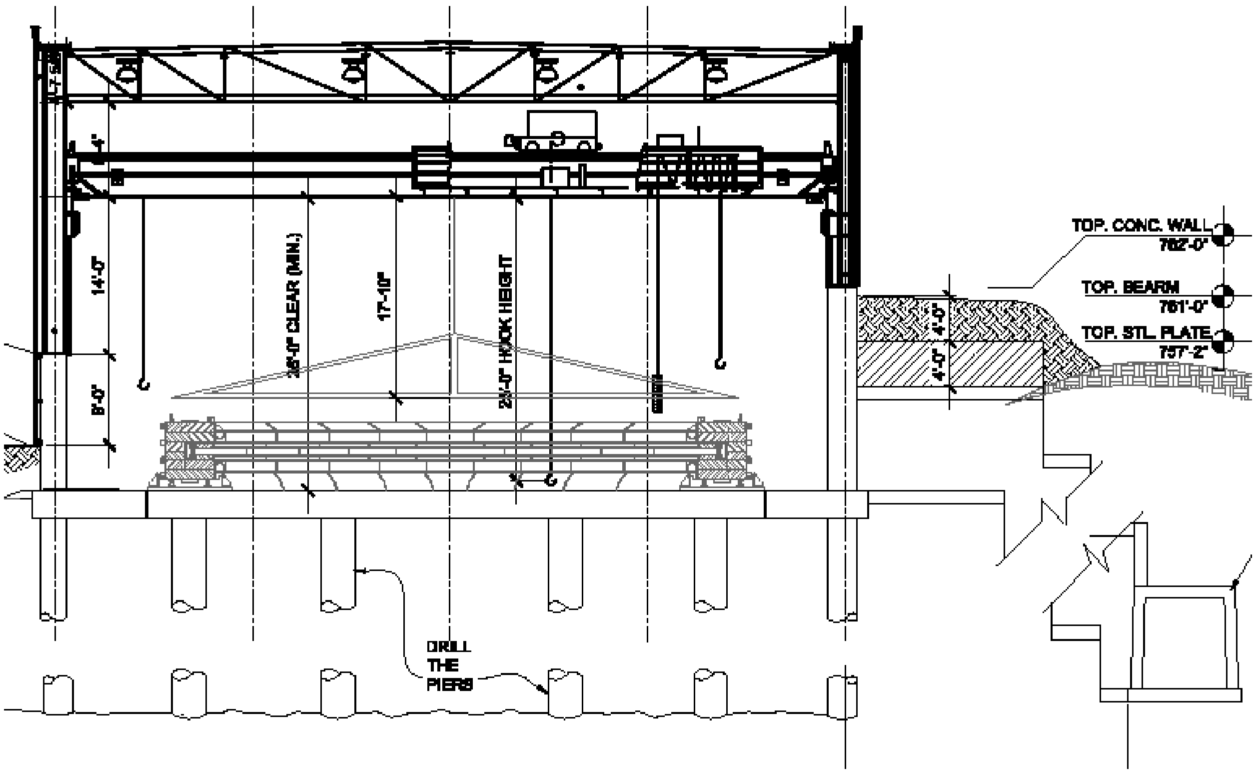


(Alber, Contreras, Huedem, Hunt, Niehoff, Stoica)

- Floor supports 650 tons via caissons down to bedrock
- Ring floor isolated from building
- Ring 4' below grade with 2'x8' additional shielding wall
- Temperature stability to +/- 2 F
- Includes new beam enclosure to bring beam up 18'
- Detailed total bldg cost $6.5M

Muon beam delivered to new building

Elevation view of new building design



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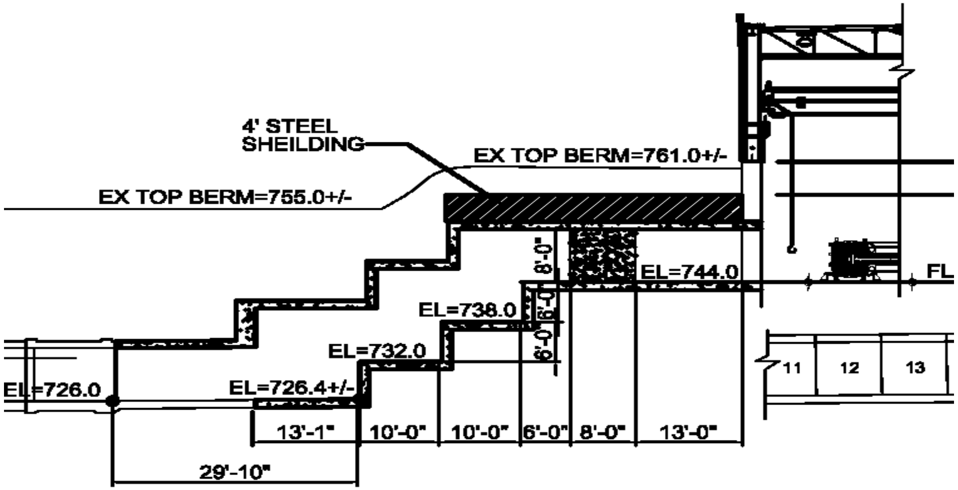
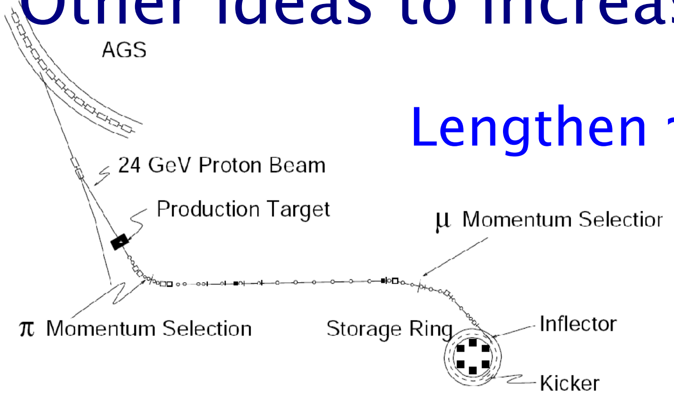
- Detailed total bldg cost $6.5M

How it might look on-site at FNAL



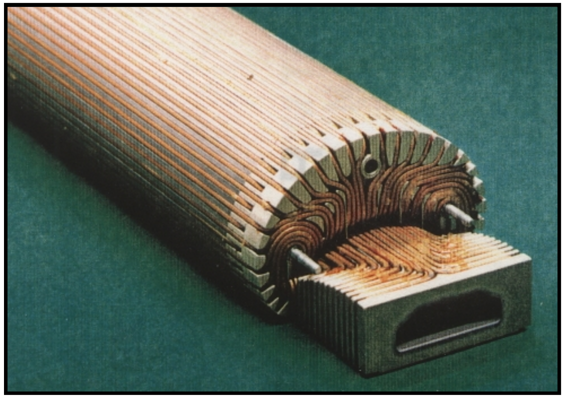
Other ideas to increase stored muons (and reduce errors)



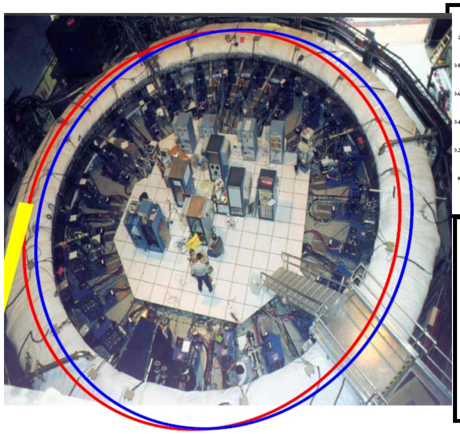
Lengthen π decay channel

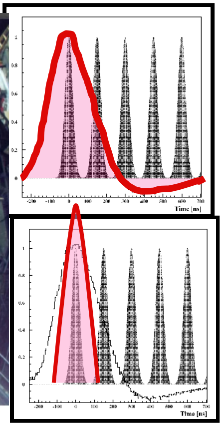
Effect	2001 [ppm]	2000 [ppm]
CBO	0.07	0.21
Pileup	0.08	0.13
Gain changes	0.12	0.13
Lost muons	0.09	0.10
Others	0.08	0.08
Total ω_a Syst Error	0.21	0.31

Goal: total sys error < 0.1 ppm



Open inflector

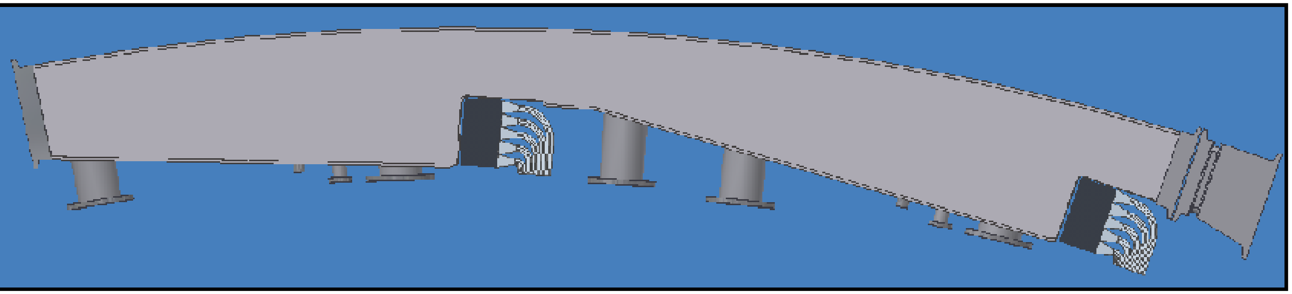


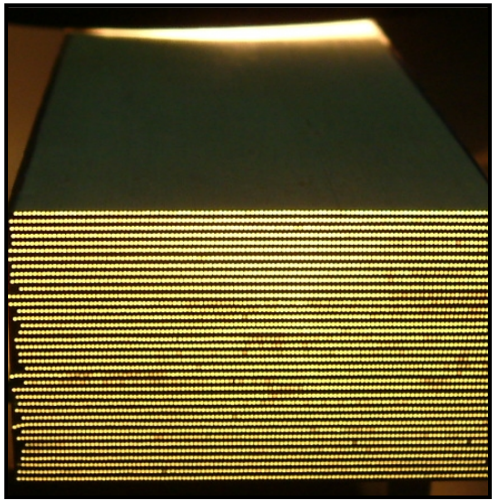


Better kicker waveform

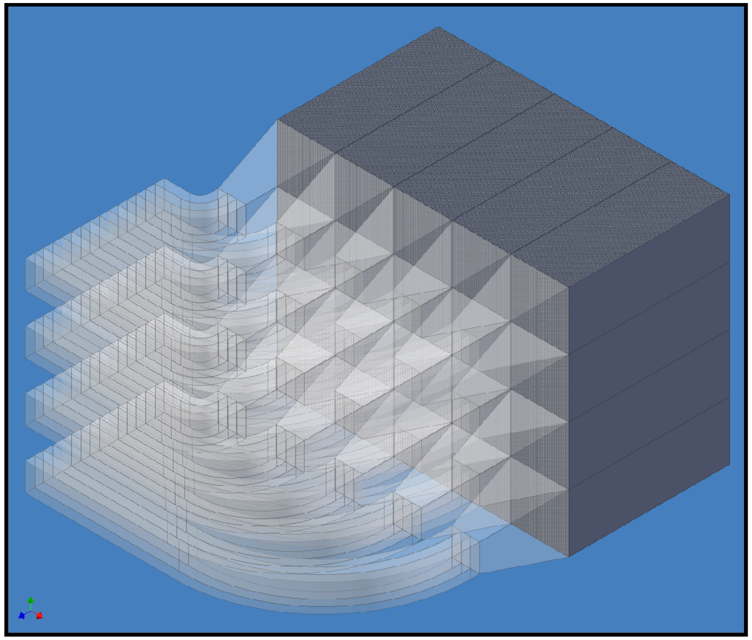
- Many other ideas to reduce errors, lots of interesting work to be done
  - Monitor muons with chambers in vacuum
  - Reduce pileup syst. with lower threshold

Spatial resolution of pileup

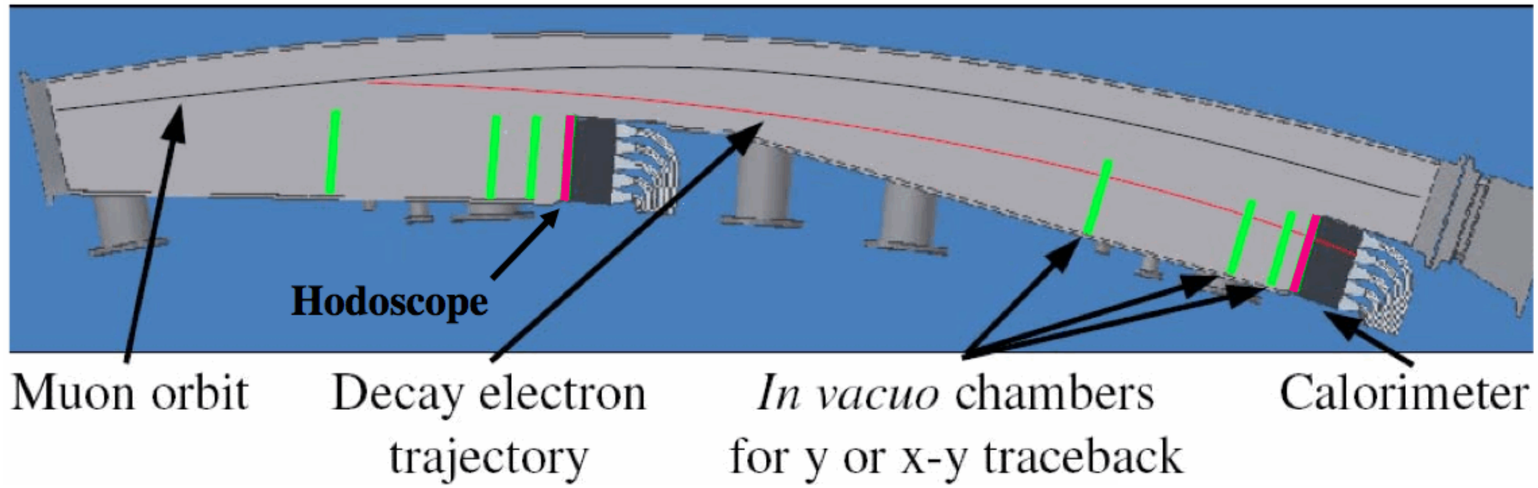




- Segmented W-SciFi calorimeter to provide ~35 cells of spatial resolution
  - Consistent with Moliere radius
  - BNL calorimeters had no segmentation
- First block constructed at Urbana and tested at FNAL MTest facility
- R&D continues on SiPM readout
- 400-500 MHz WFDs to be mounted directly on each detector station



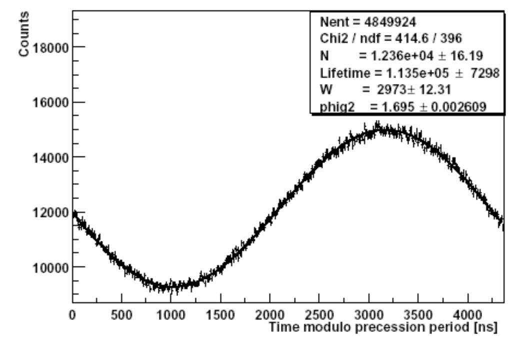
Measuring the electric dipole moment

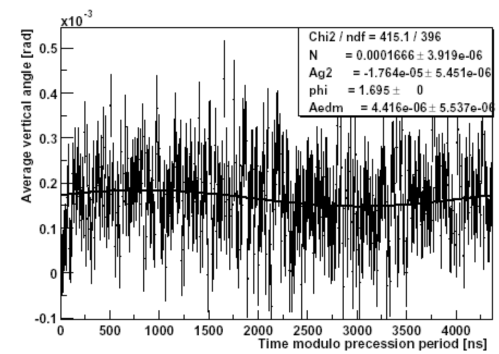


- Best limit on μ EDM comes from single straw system (outside vacuum) in BNL g-2 (Mike Sossong thesis)
  - Collected 10^7 tracks
  - Statistics limited

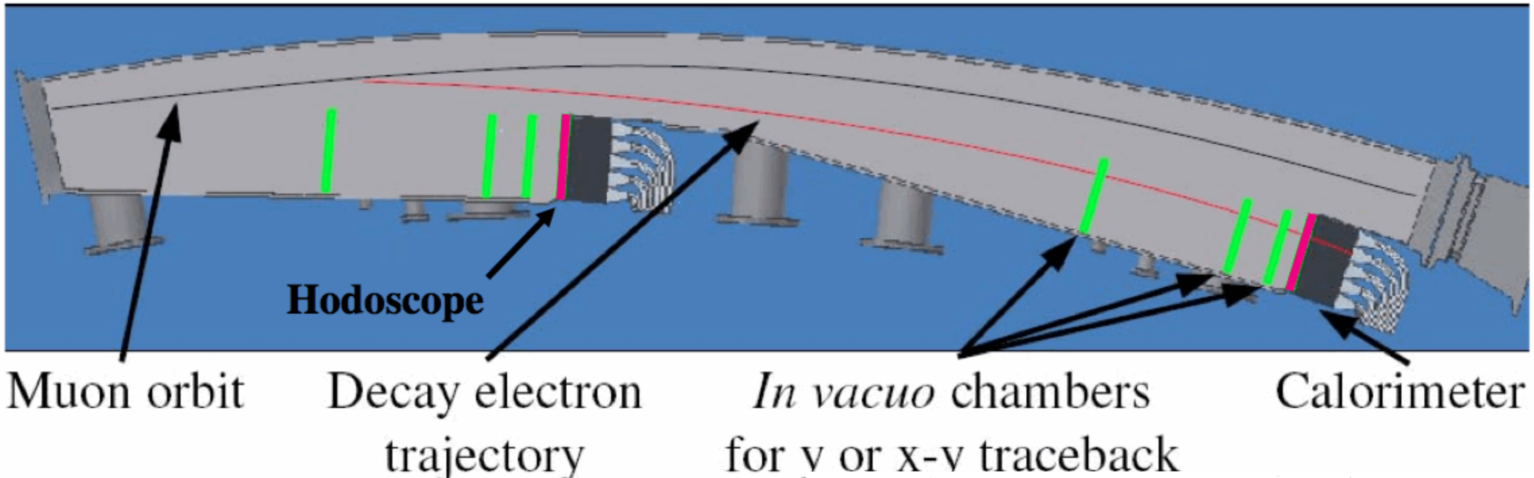
$$|d_{\mu^+}| < 3.2 \times 10^{-19}\ (e \cdot \mathrm{cm})\ (95\%\ \mathrm{C.L.})$$

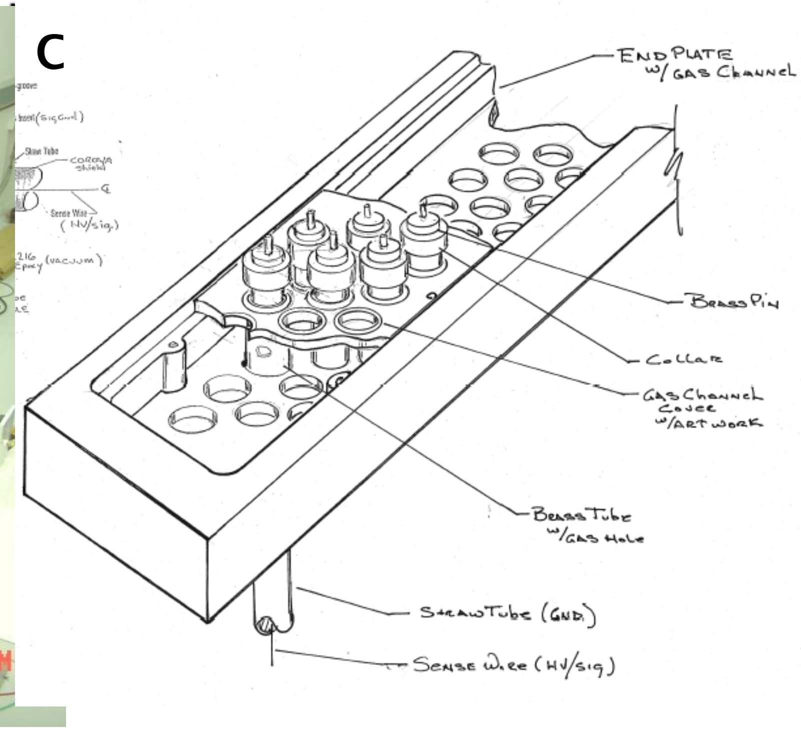
- Looking at installing 9 in-vacuo straw systems
  - Can collect $>10^{10}$ tracks
  - Minimal factor of 30 improvement in d_μ



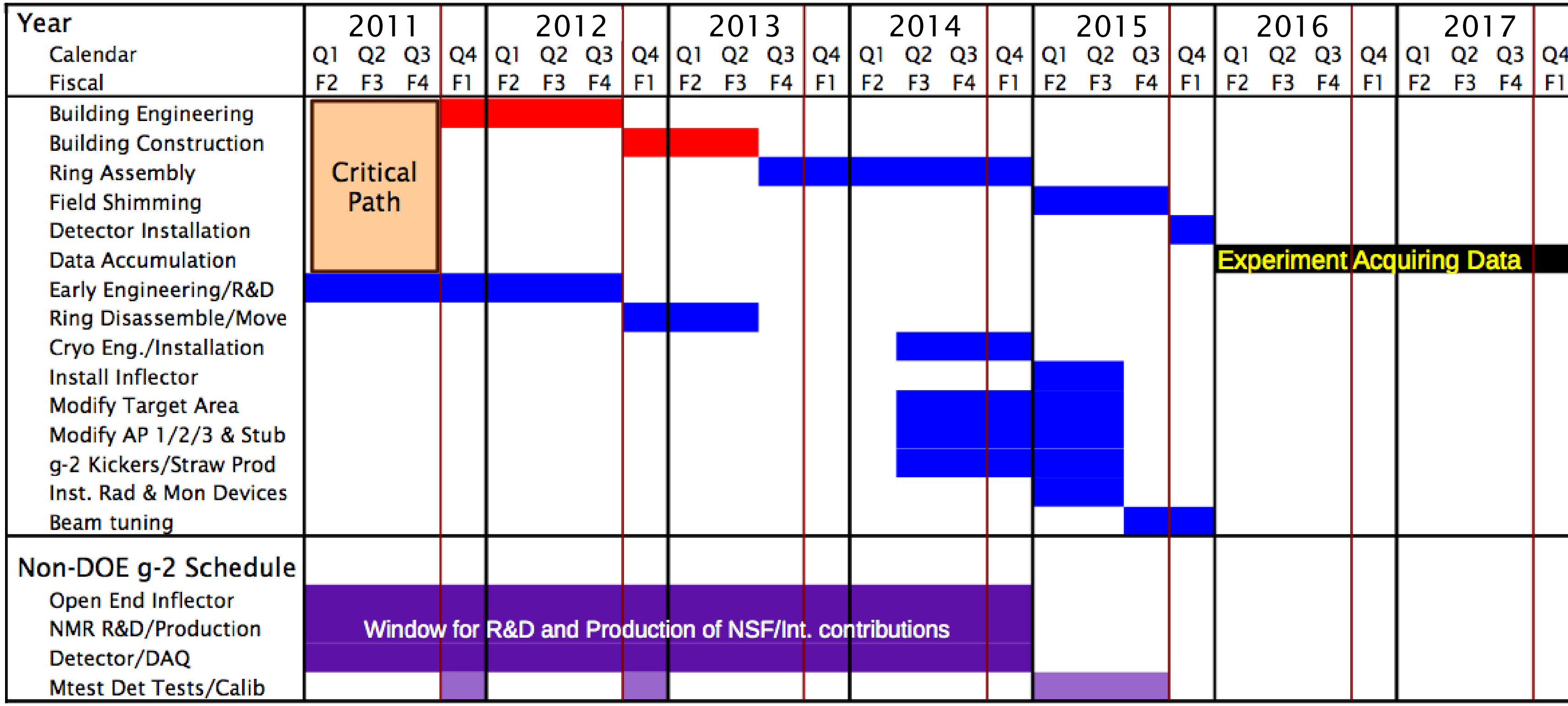


In-vacuo straw test stand at FNAL (B. Casey)



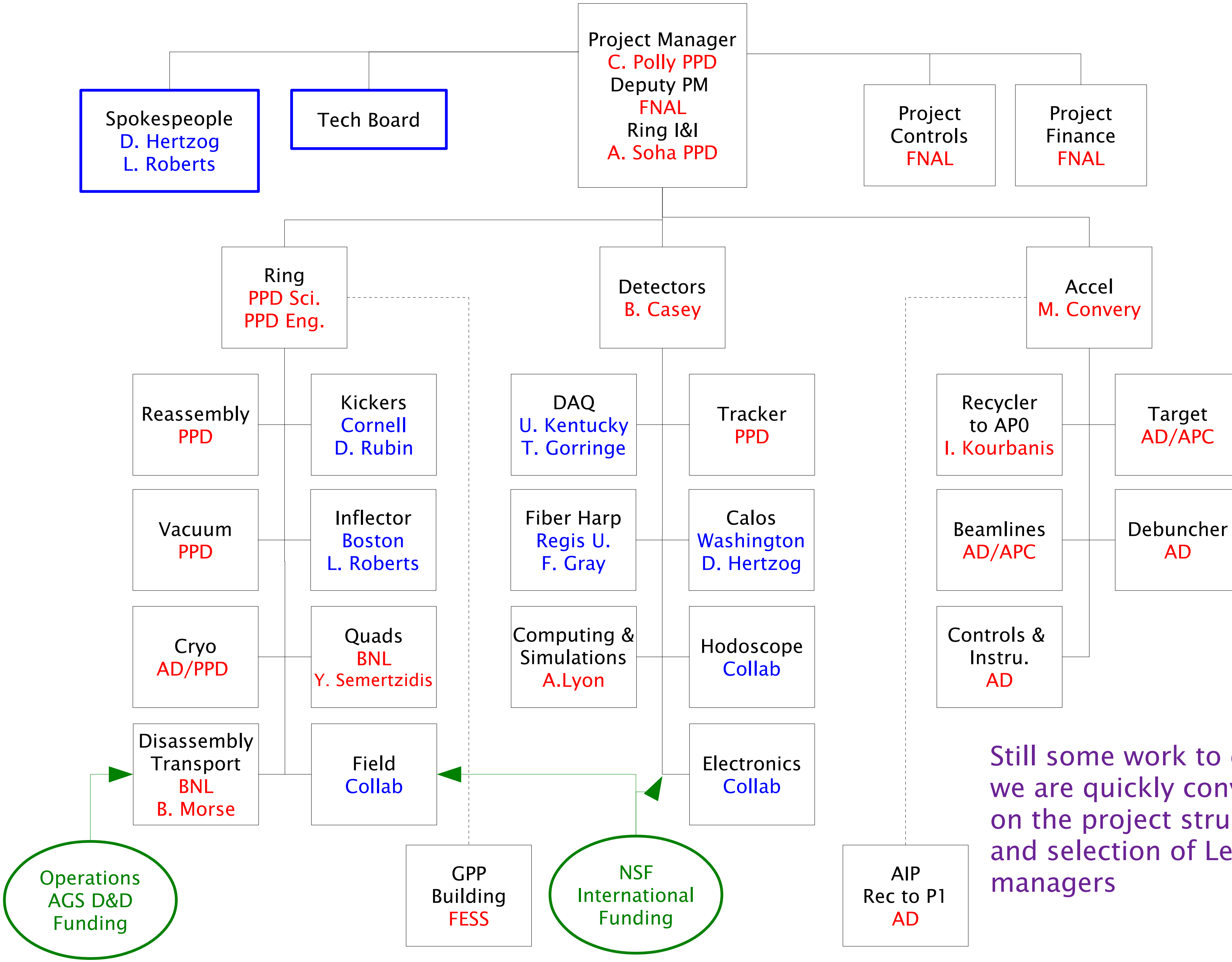


Technically-driven timeline



Working with DOE to merge CD schedule/financial constraints...

CD-0 Approve Mission Need	1st quarter FY 2012
CD-1 Approve Alternative Selection and Cost Range	3rd quarter FY 2012
CD-2 Approve Performance Baseline CD-3A Approve Limited Construction	2nd quarter FY 2013
CD-3 Approve Start of Construction	1st quarter FY 2014
CD-4 Approve Start of Operations	2nd quarter FY 2016



Still some work to do, but we are quickly converging on the project structure and selection of Level N managers

Collaboration structure

Ring Relocation
Disassembly
Transportation
Reassembly
FESS

Ring Dynamics
Inflector
Storage ring kickers
Storage ring quads
Simulation

Beam Team
Recycler mods
Transport to AP0
Targeting
Beamlines
Debuncher mods
Matching into ring

Magnetic Field
NMR systems
Fixed probes
Trolley
Absolute calibration
Shimming

Detector/Readout
Calorimeters
Straw chambers
Electronics
DAQ

Costs in proposal = 'most likely'

DOE specific costs	Cost	Cont.	Total	Source
New target	43	50%	64	Leveling
Li lens (costed) or 2 rad-hard quads	733	50%	1100	Hurh/Wolff
PMAG (pulsed or dc / rad hard)	425	50%	638	LevelingWolff
Quads in AP2	400	75%	700	Various FNAL
Debuncher, AP3 & Beamline stub	1050	75%	1838	Various FNAL
Radiological issues	67	50%	100	Collab Est.
Diagnostics	300	50%	450	Ray Committee
Moving ring	2780	75%	4865	BNL engineers
Recon ring & maintenance	3000	50%	4500	BNL engineers
Cryo for g-2 experiment	1270	50%	1905	Ray Committee
Inflector installation	504	19%	600	BNL engineers
Kicker modification	570	42%	809	BNL engineers
Fermilab Straw Detectors	385	30%	500	Ray Committee
Project management	2000	50%	3000	Ray Committee
DOE costs specific to g-2	**13526**	**55.8%**	**21069**	

Non-DOE costs specific to g-2:	Cost	Cont.	Total	Source
Detector/electronics/straws*/DAQ	3066	30%	3986	Ray Committee
Inflector	462	30%	600	Japan quote
Field probes	154	30%	200	KVI group
Non-DOE costs specific to g-2	**3682**	**30%**	**4786**	

- $6.5M for building (not shown in table)
- $12M in upgrades common to Mu2e (not shown in table)
- +$2M change in cryo assumptions, +$2M project management definition

FY11 trip to BNL

Established 3 R&D test stands
- Fiber harp detectors at Regis
- Spare kicker at Cornell
- Test vacuum chambers at Fermilab

Lots of other tasks
- Removed insulation
- Pulled first vacuum chamber
- Extracted/shipped 1/3 of calorimeters
- Cleaned out detector racks

Meeting between BNL & FNAL engineers

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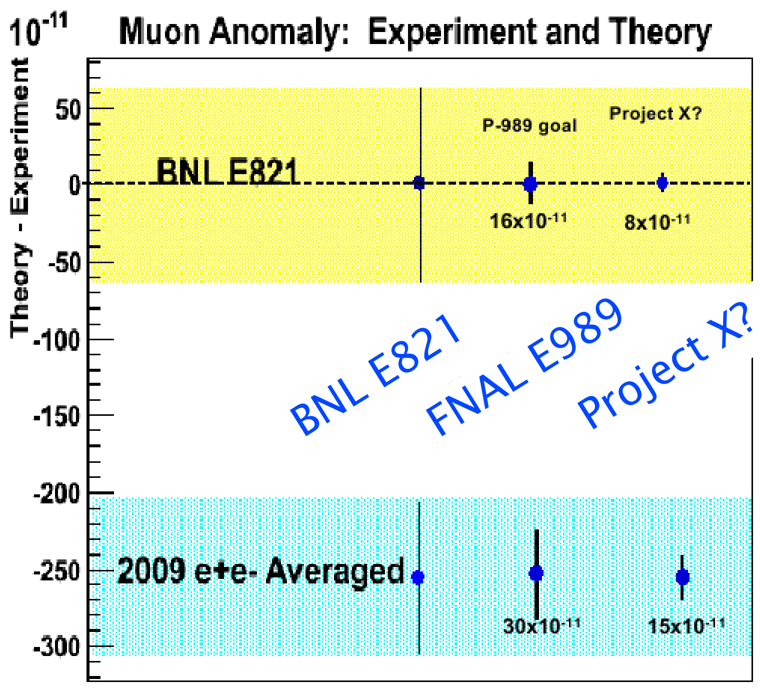
Meeting between BNL & FNAL engineers

In conclusion...

- The very successful muon g-2 program at BNL ended with a statistics-limited >3σ discrepancy in Δa_μ(exp-thy)
- Moving g-2 ring to FNAL will give necessary x21 luminosity... very complimentary to BSM probed by other efforts (LHC and Mu2e)
- With modest syst errors improvements, reduce Δa_μ(exp) from 0.56 ppm to 0.14ppm...significant resolving power for BSM theories
- Theoretical error currently limited by a_μ(had,LO), and should improve significantly after ISR and VEPP-2000, portion of HLBL measured at KLOE
- Nice fit with FNAL program, important result with a 5 year timescale

For the first time in over 60 years, we have crossed the threshold into the unknown. The experiment will be sensitive to effects that enter at 1/10th of the weak force!



Backup slides

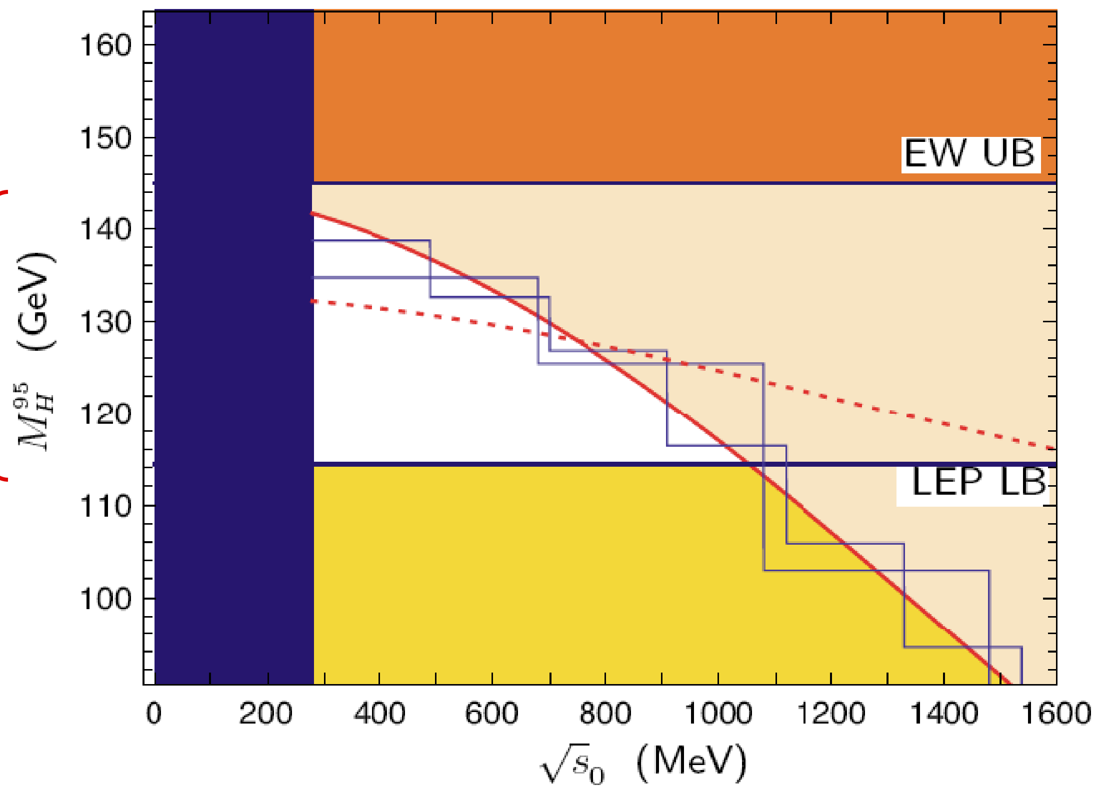
Collaboration at proposal stage...some additions since including U. Washington, Ann Arbor, ...

- Boston – electronics, beam dynamics simulations
- Brookhaven – quads, storage ring expertise
- Cornell – beam dynamics
- Fermilab – kicker, storage ring, straws, host institute, proton beams
- Illinois – beamlines, calorimeters, field quenching
- James Madison – calibration
- Kentucky – data acquisition
- Massachusetts – field shimming
- Michigan – simulations, field measurement
- Regis – fiber harp monitors
- Virginia – hodoscopes, simulations
- KVI Groningen – field team leadership, NMR systems
- LNF Frascati – calorimeter readout
- Novosibirsk BINP – beam dynamics, assembly
- St. Petersburg PNP – precision tracker
- KEK – electronics, inflector
- Osaka – detector contribution

What if the error was in σ(s)?

- How much does the M_H upper bound change when we shift $\sigma(s)$ by $\Delta\sigma(s)$ [and thus $\Delta\alpha_{had}^{(5)}(M_Z)$ by Δb] to accommodate Δa_μ ?

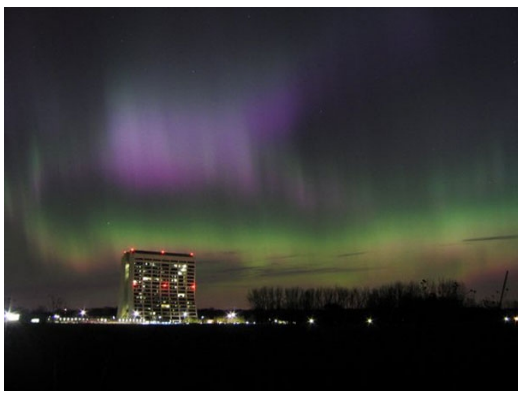
Higgs allowed



"where" to make the cross section change

Passera et al

OK, but why move to Fermilab?



- Brookhaven AGS: Hard to get more than about a factor of 10 in stored muons over original expt
- Even if we could get to x21, the instantaneous rates will make systematics difficult (many scale w/ rate)
  - Best rep rate at AGS...24 bunches in 2.7s
  - At FNAL Booster (after 15 Hz upgrade) we can use 6x4 (maybe even 8x4) bunches every 1.3s without interfering with NovA
  - If NovA is off we can go to 20x4 in 1.3s
- Additionally, since NovA is a >5 year program, there is not pressure to get the data all in 4 months
- Fits perfectly with the intensity/precision frontier that FNAL is hoping to establish over the next decade
- Perhaps even more ideas in a 2-4MW era
- From a cost perspective, really not that much more expensive due to repurposing existing infrastructure

Improvements at FNAL/BNL

Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

Stored Muons / POT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

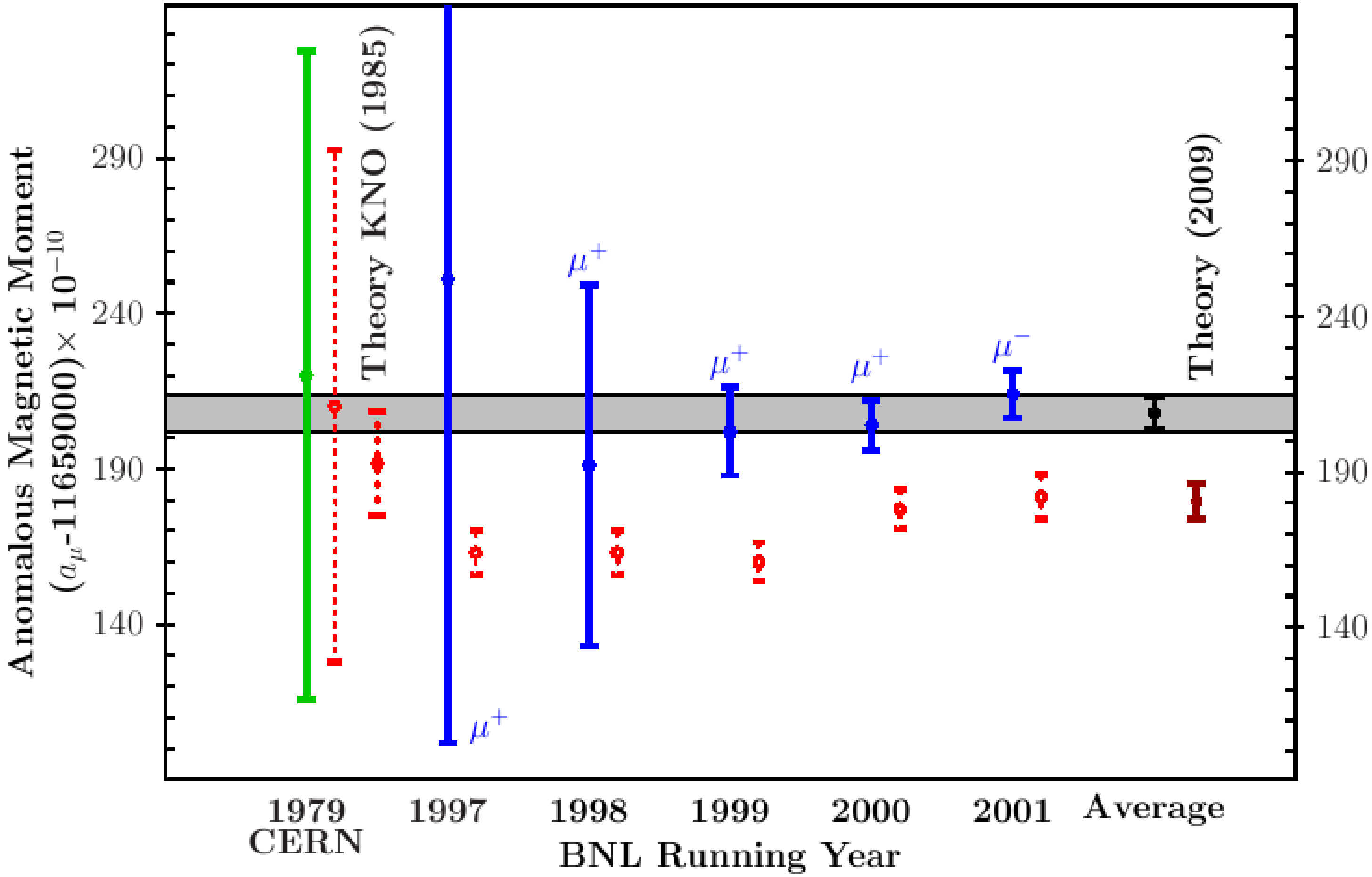
E821 Error	Size [ppm]	Plan for the New $(g-2)$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

Improvements in B field determination

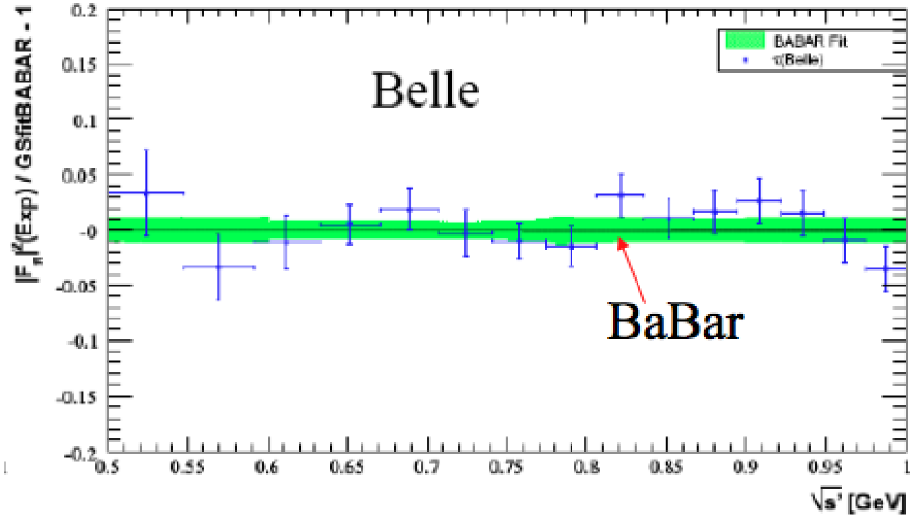
Source of Uncertainty	1998	1999	2000	2001	
Absolute Calibration	0.05	0.05	0.05	0.05	0.05
Calibration of Trolley	0.3	0.20	0.15	0.09	0.06
Trolley Measurements of B0	0.1	0.10	0.10	0.05	0.02
Interpolation with the fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	
uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Other*		0.15	0.10	0.10	0.05
Total	0.5	0.4	0.24	0.17	0.11

Theory stable for decades (modulo 1 sign error)



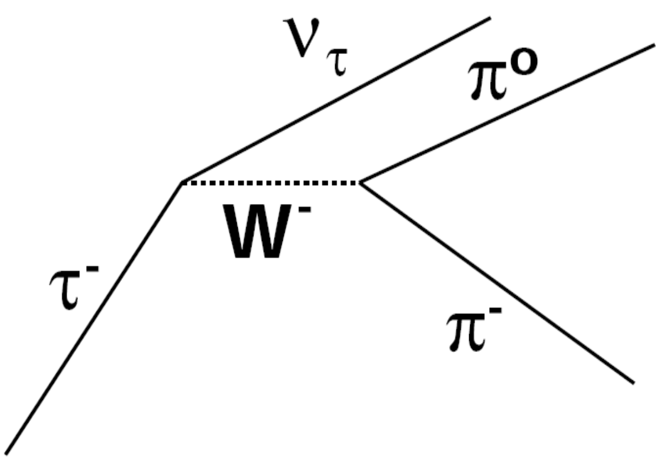
*Courtesy F. Jergerlehner, arXiv:0902.3360

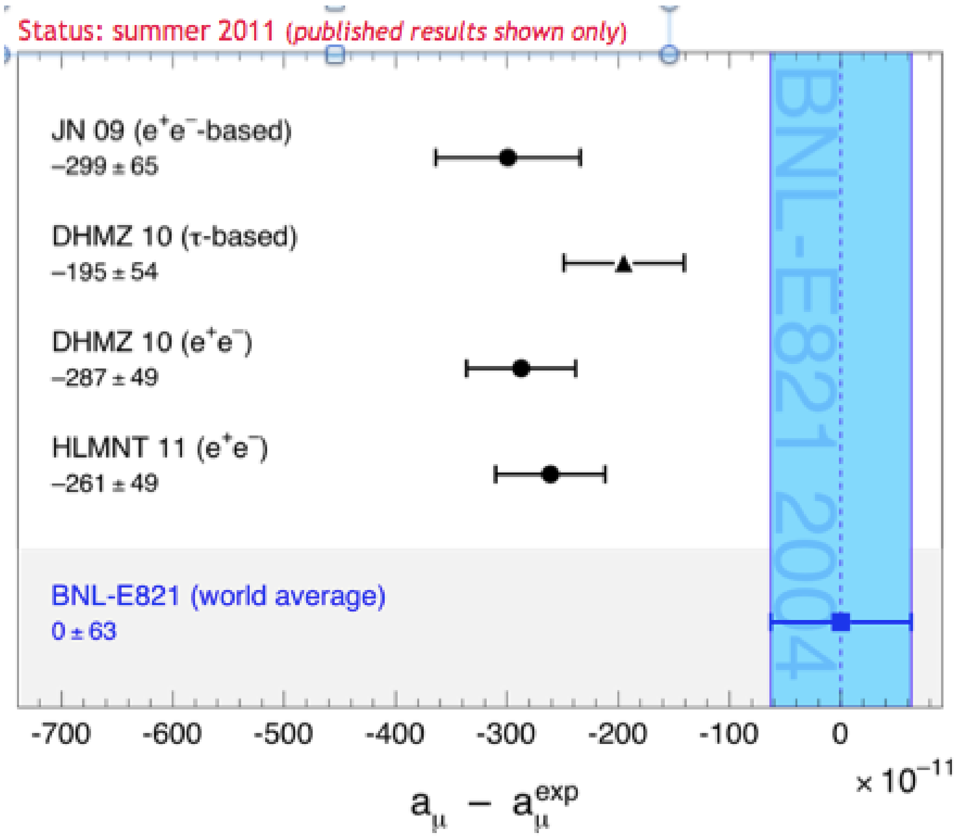
What about the τ data?



*Courtesy M. Davier, ICFA 2011

- Better isospin-breaking corrections
- More precise data from Belle and Babar
- Discrepancy with τ only 2.4σ

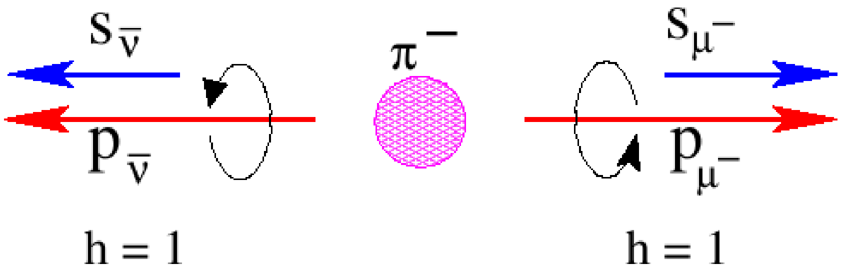




How to measure ω_a directly? Needed polarized muons.

- First we need a polarized muon source...luckily for us parity violation in the weak decay of the pion gives us a highly polarized muon source

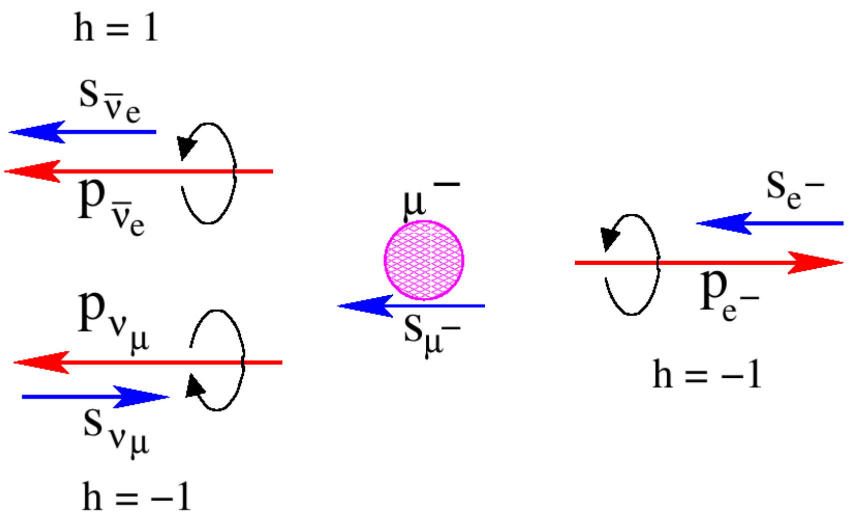
- Boosting back into the lab frame, the highest energy muons are emitted with their momentum and spin aligned with the pion momentum

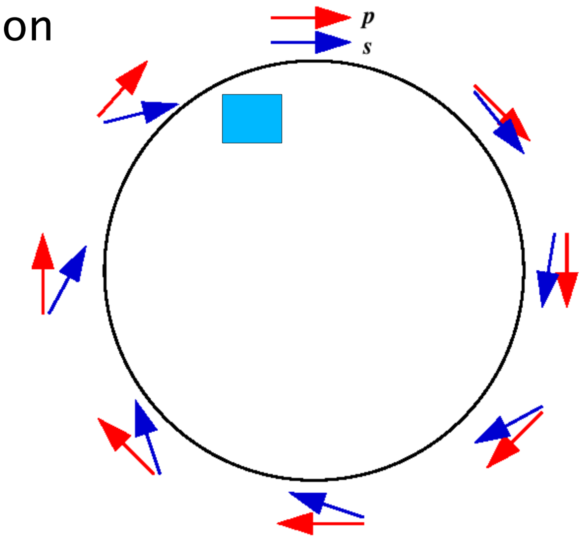


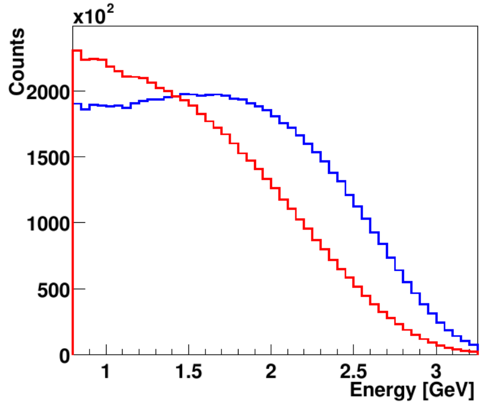
Fortuitous Physics Fact #4: Parity violation in the weak decay of the pion gives us a natural source of polarized muons.

How to measure ω_a directly? Need a polarimeter.

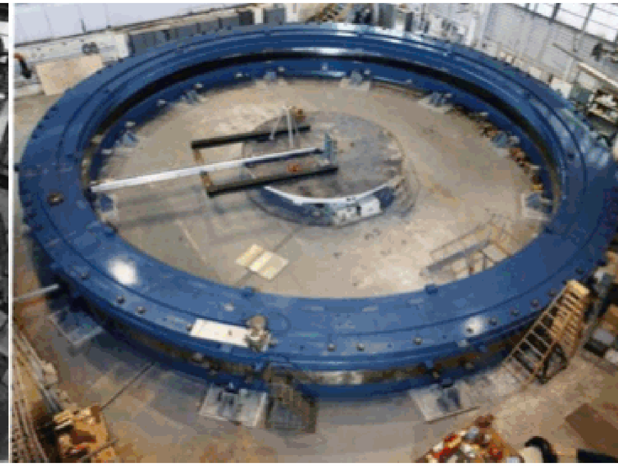
- Parity violation in muon decay results in the highest energy decay electrons being emitted parallel (or anti-parallel) to the muon

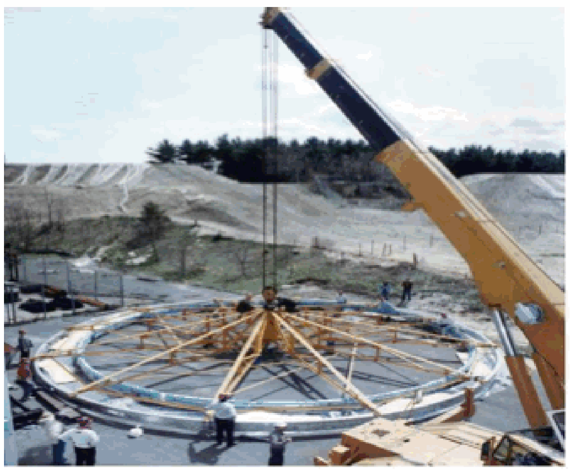
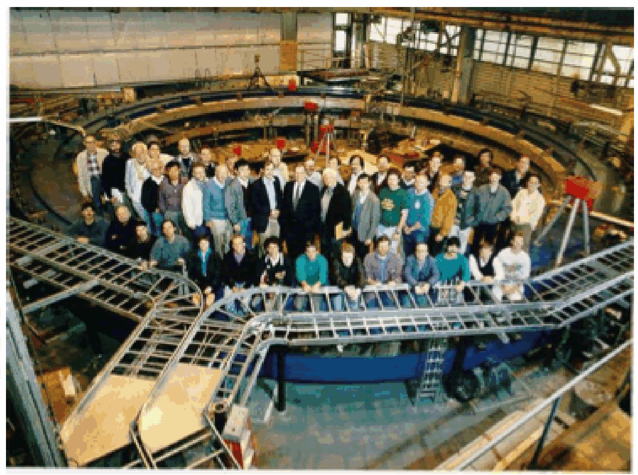
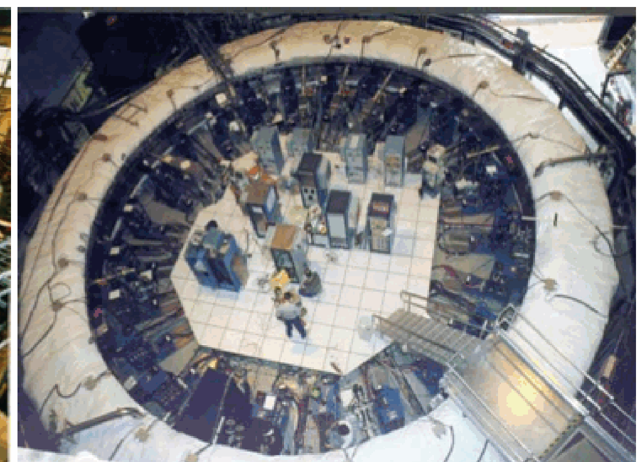




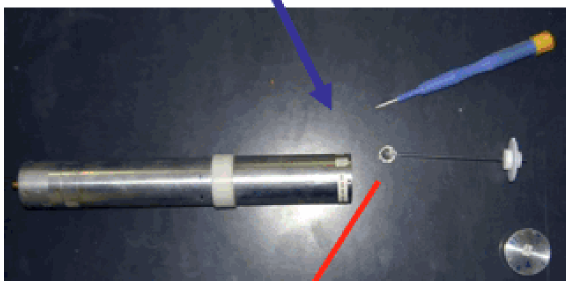


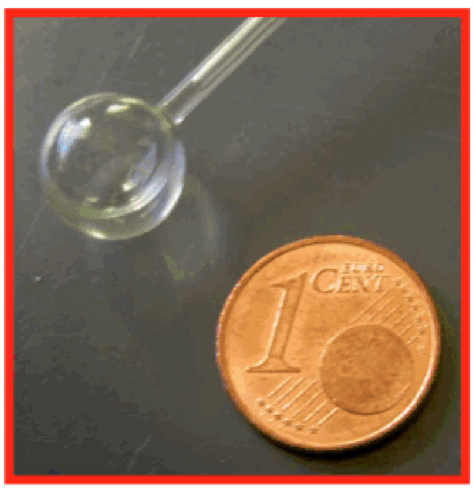
Fortuitous Physics Fact #5: Parity violation in the weak decay of the muon gives a modulation in the decay electron spectrum that oscillates at a frequency ω_a.


Scale document down


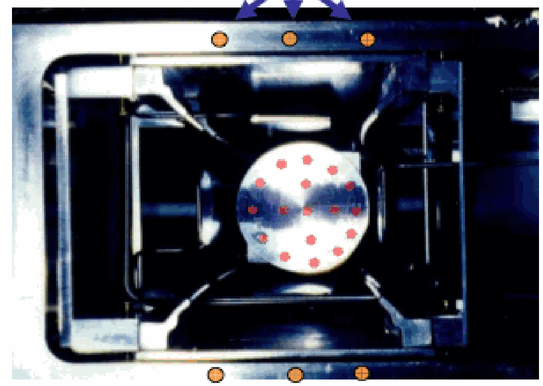




Absolute Calibration Probe:
a Spherical Water Sample

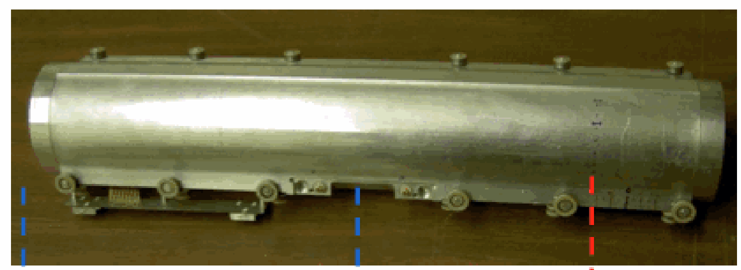




Fixed Probes in the
walls of the vacuum tank



Trolley with matrix of 17 NMR Probes



Electronics,
Computer &
Communication

Position of
NMR Probes